Integrated Performance Analysis and Optimum Fund Allocation for Capital Renewal of Healthcare Facilities

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

Healthcare facilities, including hospitals, are among the most challenging assets to maintain and modernize. An accurate performance assessment is essential for the appropriate prioritization of the subsystems that are competing for limited capital-renewal funds. Traditionally, physical condition has been the primary indicator of performance; however, other criteria have recently been added: level of service, sustainability, and risk, all of which are crucial for hospital buildings. This research introduces a practical and efficient framework for capital renewal for hospital facilities. The framework incorporates five unique aspects: (1) a two-dimensional hierarchy that accounts for the interrelationships between the hospital systems and the hospital spaces; (2) a multi-criteria performance assessment process that combines physical condition, level of service, sustainability, and risk of failure; (3) a visual all-on-site inspection application on hand-held tablet; (4) a mechanism for efficient prioritization of capital renewal tasks; and (5) optimization process for near-optimum allocation of capital-renewal of the limited capital renewal budget. The framework assesses hospital subsystems, incorporating consideration of the service quality within the indoor spaces and their impact on related subsystems. For renewal purposes, an appropriate subsystem priority index is then computed accordingly, taking into account the multi-criteria performance of the subsystems.

Surveys of hospital maintenance experts have been used both for the collection of data for the development of the framework and for its validation. A prototype of the framework has been implemented in a user-friendly application whose performance was tested through two hospital case studies, the first of which was also employed for testing the prioritization and optimization functions of the framework. The results of six case study scenarios, with varying budget constraints and objective functions demonstrated the practicality and capability of the framework with respect to

maximizing the performance of the facility relative to any desirable performance criteria. The proposed framework re-engineers the traditional process of facility performance assessment and also significantly enhances the capital renewal process by speeding the assessment process and efficiently allocating the renewal budget to maximize the return on the investment. This framework can be easily adapted to other types of building facilities and other infrastructure assets, thus contributing to sustaining the economy and the welfare of residents.

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Last, I am enormously grateful to my family for their emotional support and encouragement throughout my studies.

To

My family

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List of Abbreviations

Symbol	Definition
AHP	Analytical Hierarchy Process
AHU	Air Handling Unit
AI	Artificial Intelligent
ALOS	Asset Level of Service
APWA	The American Public Works Association
ASCE	American Society of Civil Engineers
BPI	Building Performance Indicator
CCTV	Closed-Circuit Television
CI	Condition Index
CMMS	Computerized Maintenance Management Systems
CSCE	Canadian Society of Civil Engineers
CT	Computed Tomography
FHWA	The Federal Highway Administration
GA	Genetic Algorithms
GDP	Gross Domestic Product
GIS	Geographical Information Systems
HVAC	Heating, Ventilation, and Air Conditioning
ICU	Intensive Care Unit
IEQ	Indoor Environmental Quality
ir	Interest Rate
KPIs	Key Performance Indicators
LCCA	Life Cycle Cost Analysis
LEED	Leadership in Energy and Environmental Design
LOS	Level of Service
MHLTC	Ministry of Health and Long Term Care

N/A	Not Applicable
OBPI	Overall Building Performance Index
OECD	Organization of Economic Cooperation and Development
OSD	Overall Subsystem Deficiency
OSI	Overall Subsystem Importance
OSPI	Overall Subsystem Priority Index
RBM	Risk-Based Maintenance
RI	Relative Importance
TAC	The Transportation Association of Canada
UK	United Kingdom
US	United States

Chapter 1

Introduction

1.1 Background

Civil infrastructure assets (roads, bridges, schools, hospitals, and water/sewer networks) are the foundation of a country's economic growth and the consequent prosperity of its citizens. However, a large percentage of North American and global civil infrastructure, assets are deficient because of deterioration due to age and harsh environmental conditions and because of insufficient capacity (Vanier and Rahman 2004a). In the United States (US), the backlog in projected infrastructure increased from US$1.6 trillion in 2005 to US$3.6 trillion in 2013 (American Society of Civil Engineers (ASCE) 2013) (Table 1.1).

Table 1.1: ASCE report cards for the US infrastructure (2005, 2009, and 2013)

Infrastructure Category	Report Card for America's Infrastructure 2005	Report Card for America's Infrastructure 2009	Report Card for America's Infrastructure 2013
Aviation	D+	D	D
Bridges	C	C	C+
Dams	D	D	D
Drinking Water	D-	D-	D
Energy	D	D+	D+
Hazardous Waste	D	D	D
Navigable Waterways	D-	D-	D-
Public Parks & Recreation	C-	C-	C-
Rail	C-	C-	C+
Roads	D	D-	D
Schools	D	D	D
Security	I	Not included	Not included
Solid Waste	C+	C+	B+
Transit	D+	D	D
Wastewater	D-	D-	D
Levees	Not included	D-	D-
America's Infrastructure G.P.A	D	D	D+
ESTIMATED 5-YEAR REQUIRED INVESTMENT	$ 1.6 Trillion	$ 2.2 Trillion	$3.6 Trillion
A= Exceptional; B= Good; C= Mediocre; D= Poor; F= Failing; I=Incomplete			

In Canada as well, it is estimated that 79 % of the infrastructure was already beyond its anticipated service life (Canadian Society of Civil Engineers (CSCE) 2003); as of 2006, Canada's infrastructure deficit was about CAN$125 billion (Mirza 2006). Statistics also indicate that non-residential buildings represent the largest infrastructure sector in both Canada and the US, as shown in Figure 1.1 (Statistics Canada 1995; US Census Bureau 1999; Elhakeem 2005). This sector is consequently expected to show the largest shortfall with respect to expenditures for rehabilitation and repair (Elhakeem 2005).

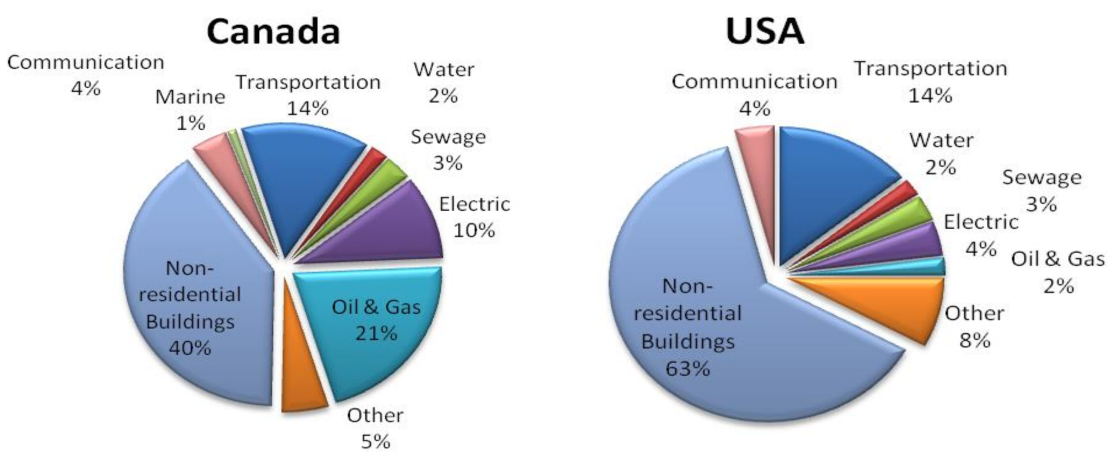

Figure 1.1: Average yearly expenditures by type of infrastructure

The majority of non-residential buildings are educational buildings and healthcare facilities: the latter are the focus of this study. This category includes a wide range of structures, from simple clinics to large complex hospitals. The US healthcare industry is a $2.8 trillion industry, accounting for about 17 % of the entire US gross domestic product (GDP) (Frampton et al. 2003). Moreover, to accommodate the increasing demand created by a growing population, it was estimated in 2004 that $300 billion would need to be spent on US hospital construction between 2005 and 2020 (Ulrich and Quan 2004).

Hospital buildings represent an essential component of healthcare systems and play a vital role in patient care (Sherif 1999). Dynamic, complex, and costly to both operate and maintain, hospitals generally provide two broad services: diagnosis and treatment, both of which require specialized laboratories, imaging devices, emergency rooms, and operating theatres. Hospitals also house support services, such as food and housekeeping (James and Noakes 1994; Sherif 1999), and include a number of highly complicated interdependent systems, such as mechanical, electrical, and communication systems, all of which must provide uninterrupted 24-hour service (Monti and Nuti 1996; Shohet et al. 2003). Because they consume large amounts of energy and water, and produce a sizeable quantity of unrecyclable waste, these facilities also have a significant impact on the surrounding environment. All of these considerations are magnified by the size of the healthcare sector, which in Canada is very large, including a total of 766 hospitals, distributed as shown in Figure 1.2.

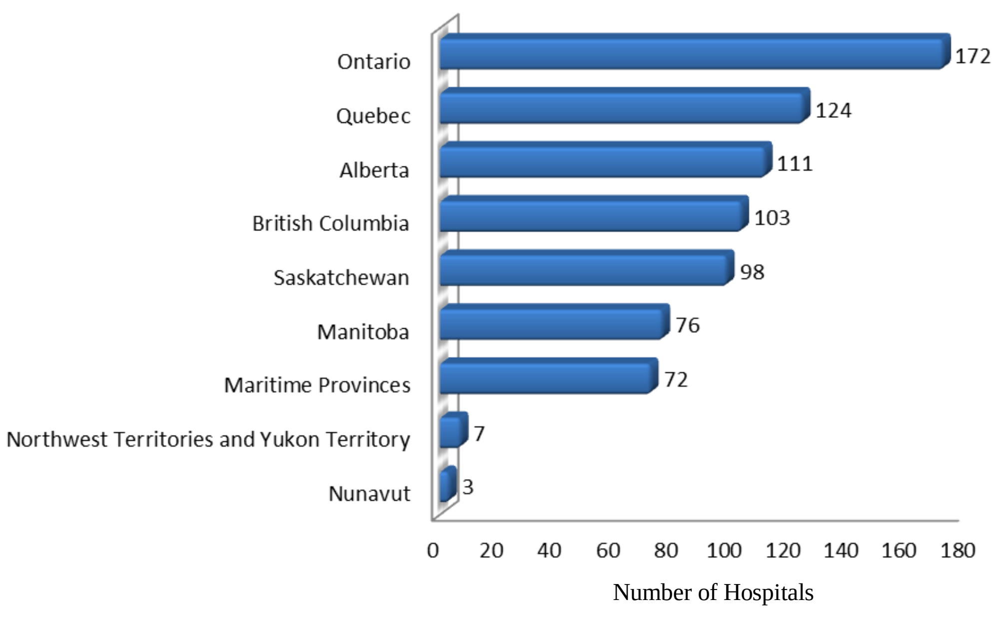

Figure 1.2: Distribution of hospitals in Canada (Guide to Canadian Healthcare Facilities 2007)

1.2 Challenges of Hospital Asset Management

Many organizations typically manage their infrastructure assets using two complementary functions: maintenance/repair activities that sustain day-to-day operation and capital renewal programs for renewing or replacing existing assets in order to keep the inventory healthy and to add to or extend the functionality or location of services. While both functions are challenging, facility renewal involves a wider tactical and strategic scope and is thus more complex. In general, however, poor management of hospital assets affects the quality of healthcare services in a number of ways. For example, hospital-acquired infections are one of the leading causes of death in the US, killing more people than AIDS, cancer, or automobile accidents (Institute of Medicine 2001). Poorly maintained hospitals can therefore be dangerous for patients, visitors, and medical staff. In general, the performance of the subsystems and the quality of the indoor environment are critical for hospital users. For example, improperly maintained heating, ventilation, and air conditioning (HVAC) systems can be a source of contamination (Frank 1995). Improper lighting has also been correlated with patient depression and with medication errors. Excessive noise upsets patients, causing increased stress and lack of sleep (Pommer and Horman 2008). An important goal of a healthcare facility manager should therefore be to eliminate any deficiencies in hospital operation because of the effects of poor maintenance with respect to fatalities and substantial economic loss (Frank 1995).

Effective asset management is thus essential for the provision of efficient healthcare service (Shohet et al. 2002; Shohet et al. 2003). In recent years, at the research and commercial levels, a variety of systems have been developed as a means of supporting either the maintenance or renewal of assets. With respect to maintenance, surveys of existing computerized maintenance management systems (CMMSs) have shown them to be mature and useful for managing work orders, trouble calls, and preventive maintenance schedules; however, this important information is seldom utilized as support for asset renewal decisions (Vanier 2000). On the asset renewal front, on the other hand, numerous systems have been created as a means of supporting decisions related to inspection, asset prioritization, and fund allocation. Surveys of municipal asset management systems (Halfawy et al. 2005) have revealed that, despite their powerful capabilities that include databases, computer-aided design (CAD), and geographical information systems (GIS), they generally lack integration with CMMS systems, defined performance metrics, and optimization features. The benefits provided by existing systems are often offset by the numerous technical challenges related to performance evaluation, the optimization of renewal decisions, and the execution of capital renewal programs. In addition, capital renewal budgets are becoming increasingly restricted at the same time that regulatory demands for infrastructure sustainability are entailing difficult requirements related to waste reduction, the utilization of natural resources, and improvements in the socio-economic return on infrastructure spending. These challenges have contributed to diminished service satisfaction, a high risk of failure, and a large backlog in renewal spending.

1.3 Research Motivation

This research was motivated by a desire to address the specific challenges related to asset management for hospital buildings. The specific research motivations are as follows:

1.3.1 Complexity of hospital buildings

Due to the specialized services they provide, asset management for hospitals is more challenging than for other types of buildings. Elhakeem (2005) estimated that a school has about 170 subsystems to be inspected, rated, evaluated, and renewed. This number is to be similar or greater for hospitals due to additional specialized systems such as medical gas systems, operating rooms, and nurse-call systems. The efficient management of hospital buildings requires detailed performance analysis of all of these systems and subsystems.

1.3.2 Need for practical performance indicators

Capital renewal decisions have traditionally been based on a cost-benefit analysis, in which physical condition is considered to be a primary indicator of benefit. Other views have recently been examined, including multiple-criteria performance analysis (Shohet 2006; Shohet and Lavy 2004); level of service (LOS) attained from the perspective of multiple stakeholders (Nasser 2007); risk/reliability analysis for the reduction or elimination of the consequences of failure (Christodoulou et al. 2009; Moubray 1997); and social, economic, and environmental sustainability (Lützkendorf and Lorenz 2005). These approaches vary with respect to level of detail, time and cost of the analysis, and suitability for specific assets or asset subsystems. Because complex assets such as healthcare facilities involve hundreds of civil, architectural, electrical, and mechanical subsystems, a hybrid approach that incorporates multiple techniques is necessary.

From another perspective, the existing research on healthcare performance indicators has been focused primarily on the prioritization of maintenance activities based on operational factors: the age of the building, the number of beds, patient throughput, energy efficiency, fire safety, comfort, and spatial efficiency (Al-Zubaidi 1997; Shohet and Lavy 2004). In more recent research on healthcare facility renewal (Lavy and Shohet 2007; Shohet 2006), the increased performance required by users and owners mandated the additional consideration of strategic factors that impact renewal decisions. The lessons learned from hospital case studies (Al-Zubaidi 1997; Hosling and Jarvis 2003) have also provided the basis for a discussion of the need to consider other factors in facility renewal, including market, demographic, technical, financial, legal, and organizational constraints. Moreover, because medical facilities cannot be interrupted abruptly and, when renewed, must be restored to a functional condition as quickly as possible (Al-Zubaidi 1997), two other requirements are mandatory: using a risk-based approach for critical components that have zero tolerance (Cristodoulou et al. 2009) and maintaining facility operation as a constraint during the execution of renewal plans. This discussion has identified a need for the clear definition of key indicators related to four categories of performance, as they apply to various healthcare components: condition indicators, LOS indicators, sustainability indicators, and risk indicators.

1.3.3 Need for efficient prioritization and fund-allocation decisions

Capital renewal funds are normally allocated to asset subsystems based on priorities that are established in two ways: either substantially based on experience or calculated based on the performance evaluation. The process basically involves the allocation of funds based on a single ranking of the subsystems, which is relatively unstructured process. As an example, to allocate hospital renewal funds, the Ministry of Health and Long Term Care (MHLTC) uses a simple allocation model that is a direct percentage of the hospital's operating funds in past years (MHLTC 2008). This simple model does not include consideration of important performance indicators such as the stakeholders' satisfaction with hospital services, the availability of newer technology to improve services, patient demographics at the specific hospital location, energy-saving and environmental issues, and the business value retained and passed on to subsequent generations. Guidance is also not given to individual hospitals with respect to key performance indicators that support internal decisions about when and how to renew which subsystems in order to avoid the risk of critical equipment failure and to increase the level of service satisfaction for all stakeholders, including patients and staff.

Because of the inefficiency of the allocation of funds based on heuristic ranking, substantial benefits can be derived from prioritization based on performance assessment. The deployment of a performance-based prioritization framework for hospital capital renewal, however, is a complex task, particularly when hundreds of subsystems are involved.

1.4 Research Objectives and Scope

The overall goal of this research is to develop a practical and comprehensive framework to support and enhance efficient performance assessment and optimum fund allocation for healthcare facilities. The detailed objectives are as follows:

- Develop a hospital building hierarchy that integrates physical systems/subsystems and functional zones/spaces; as a more representative indicator of the assessment needs of hospitals;
- Identify and use essential key performance indicators (KPIs) for quantifying the physical condition, LOS, sustainability, and risk of failure for all systems and subsystems;
- Develop a mechanism for assessing the indoor environment quality (IEQ) within functional spaces (in terms of water, air, lighting, and noise), and quantify the corresponding impact of the IEQ on the LOS and renewal priority for affected systems;
- Develop a method of priority analysis that computes performance indices at all levels of the hospital hierarchy, and combine it with a visual system on a handheld device that enables faster, less expensive, and less subjective hospital inspection;
- Develop an optimization framework that integrates deterioration prediction, renewal options and costs, and life cycle cost analysis to support capital renewal planning; and

- Verify the developed framework through surveys of expert professionals, and demonstrate its usefulness through case studies.

The research presented in this thesis supports decisions related to the prioritization of hospital systems and subsystems for renewal purposes in order to maximize the return on capital renewal funds. The direct outcome of the research is a generic performance assessment framework with a computerized prototype that is appropriate for healthcare facilities in general and hospitals in particular, which can be adapted to any other building type. The framework will greatly contribute to enhanced healthcare management and ultimately to the cost-effective sustainability of infrastructure services.

1.5 Research Methodology

To achieve the above objectives, the approach followed in this research consisted of the following steps, as shown in Figure 1.3:

1. Conduct an extensive literature review of asset management systems and performance assessment, including techniques, software, and models.
2. Develop a practical hierarchy that integrates the functional zones/spaces and the systems/subsystems in a hospital building.
3. Identify KPIs that best describe the performance of each subsystem in a hospital building.
4. Develop IEQ factors: air quality, water quality, lighting intensity, and noise.
5. Develop a visual inspection tool based on the use of a handheld device that will make the field inspection process faster, easier, and less expensive.

6. Develop a survey questionnaire in order to identify the relative importance of the functional zones, spaces, systems and subsystems; the KPIs for each subsystem; and the IEQ factors.
7. Store all inspection data directly to a spreadsheet.
8. Conduct a field study in order to determine an appropriate real-life case.
9. Validate and test the results of the developed assessment and prioritization framework.
10. With the use of a genetic algorithm technique, develop a capital renewal optimization model that incorporates the performance and prioritization framework, a deterioration model, a renewal option, and a life cycle cost analysis.
11. Validate and test the developed capital renewal optimization model.

1.6 Thesis Organization

The thesis is organized as follows:

Chapter 1: This chapter introduces North American infrastructure (Canada and the US), the challenges associated with asset management, the research motivation, the research objectives and scope, and the research methodology.

Chapter 2: This chapter provides a review of the existing research related to the management of civil infrastructure assets in general and of healthcare facilities in particular. It also includes an analysis of the available performance indicators for hospital buildings, the functions of asset management, and the current practices for prioritizing maintenance activities and allocating limited capital renewal funds.

Chapter 3: This chapter discusses the developed performance assessment framework, together with its components for prioritizing subsystems for renewal plans, and explains the calculation of 1) the overall subsystem indicator (OSI); 2) the overall subsystem deficiency (OSD); 3) the overall subsystem priority index (OSPI); and 4) the overall building performance index (OBPI).

Chapter 4: This chapter introduces the developed questionnaire survey parts, the case studies that have been conducted, and the data analysis for the collected data.

Chapter 5: This chapter introduces the performance assessment for two case studies using the developed framework. The maintenance practice, visual inspection results, prioritization results, and overall building performance calculations for each case study are also introduced.

Chapter 6: This chapter discusses the capital-renewal optimization model that integrates the performance assessment, deterioration model, renewal and improvement model, and fund allocation optimization. Testing and validation of the developed model and the additional fund allocation experiments are also introduced.

Chapter 7: This chapter introduces the summary and conclusions, research contributions, and the future research

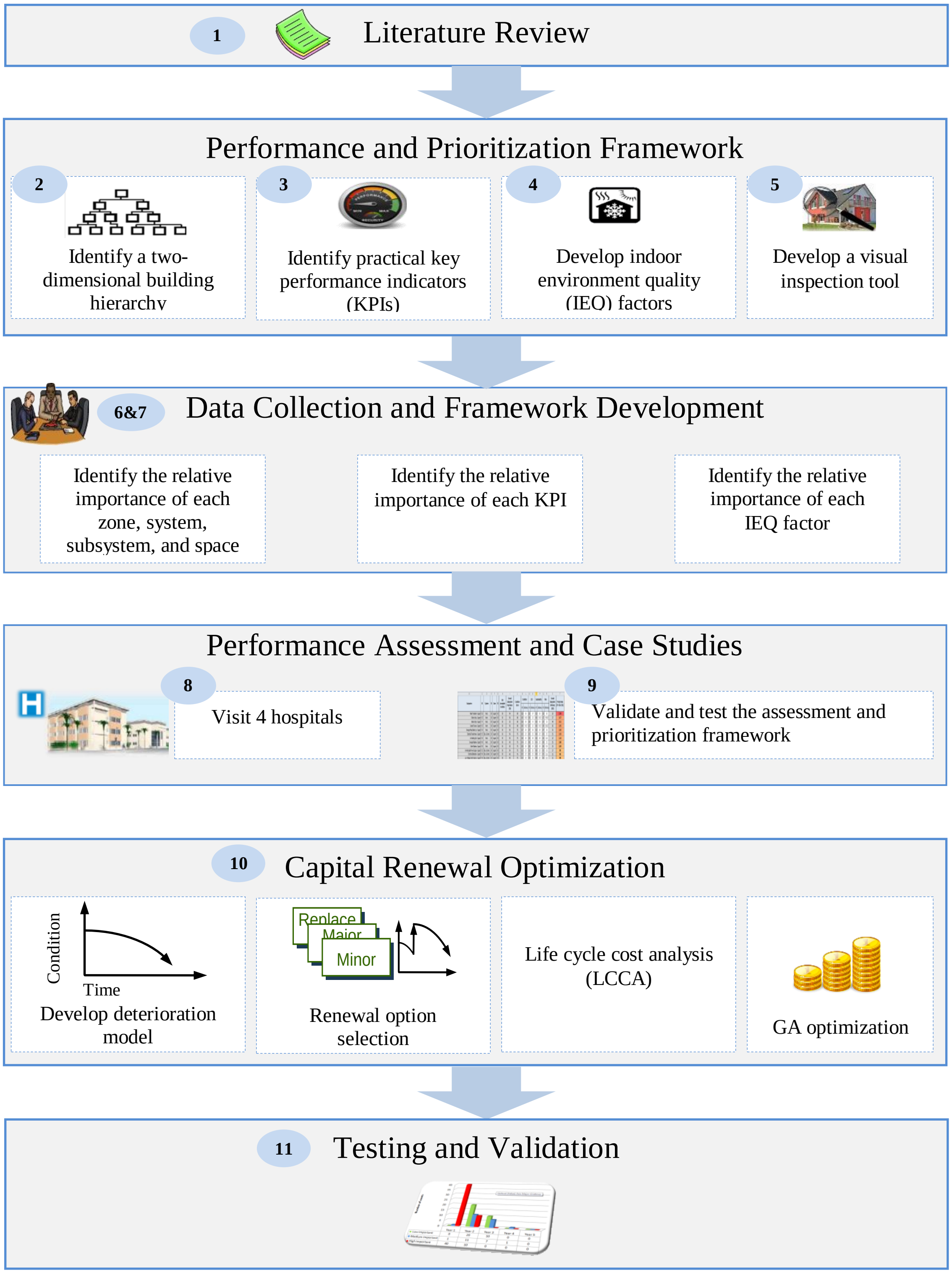

Figure 1.3: Research methodology

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Chapter 2

Literature Review

2.1 Introduction

This chapter provides a literature review of the existing research related to the management of civil infrastructure assets in general and of healthcare facilities in particular. It also includes an analysis of the available performance indicators for hospital buildings, the functions of asset management, and the current practice for prioritizing maintenance activities and allocating limited capital renewal funds.

2.2 Civil Infrastructure Assets

As shown in Figure 2.1, civil infrastructure assets consist of constructed physical facilities: buildings, transportation systems, energy production and distribution systems, recreation facilities, water and waste water systems, airports, and communication networks. Total infrastructure assets in the US are valued at US$30 trillion and in Canada are worth US$5 trillion (Vanier 2001). These important assets touch almost all aspects of life and form the foundation of modern society as well as that of national and local economies worldwide (Karlaftis and Peeta 2009). Well-maintained infrastructure assets can therefore substantially increase a country's competitiveness in a global economy.

Despite their importance, as a result of population growth, limited funding, severe climate conditions, poor quality control, poor materials, and inadequate inspection and maintenance, civil infrastructure assets are deteriorating faster than they are being renewed (Vanier 2001). All of these factors accelerate the deterioration of infrastructure assets and correspondingly increase the probability of their failure if adequate maintenance and/or renewal works are not carried out during their life cycles.

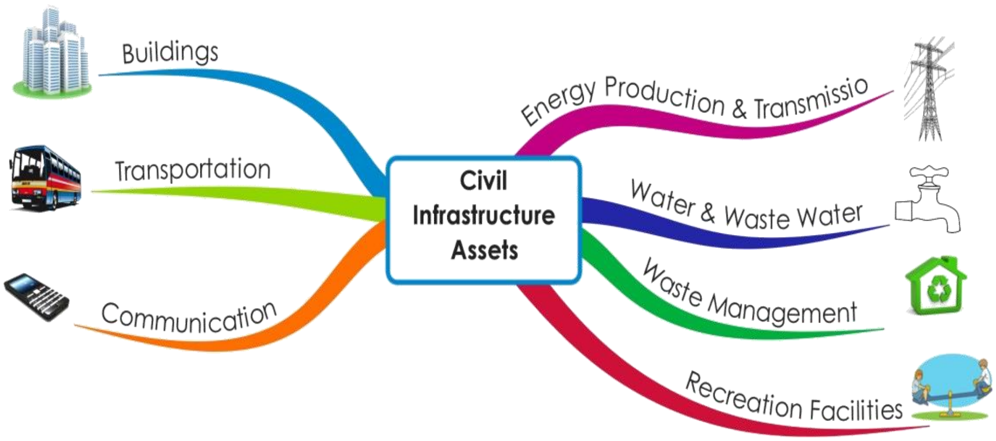


Figure 2.1: Civil infrastructure assets (based on Hudson et al. 1997)

Inadequate maintenance can result in unplanned asset failure (Moore and Starr 2006), which occurs when a component can no longer be relied upon to fulfill its principal functions (Ayininuola and Olalusi 2004). Such failures can have consequences that include not only deaths and injuries but also economic losses. Infrastructure assets must therefore be continually well maintained in order to ensure their effective performance. To support difficult decisions related to asset maintenance and renewal, extensive research in the domain of asset management has been conducted over the past few decades, as discussed in the following section.

2.3 Asset Management

To sustain the serviceability and safety of large networks of assets, a variety of asset management tools have been introduced over the past two decades to help asset managers determine the most cost-effective means and timing for the repair or replacement of their existing building stock (Elhakeem and Hegazy 2010). As shown in Figure 2.2, in general, the owners of large buildings have two functions for the care of their asset inventory: preventive/reactive maintenance; and capital asset renewal. While maintenance functions support day-to-day operations, capital asset renewal, which is the focus of this research, involves the upgrading or complete replacement of the asset or some of its components.

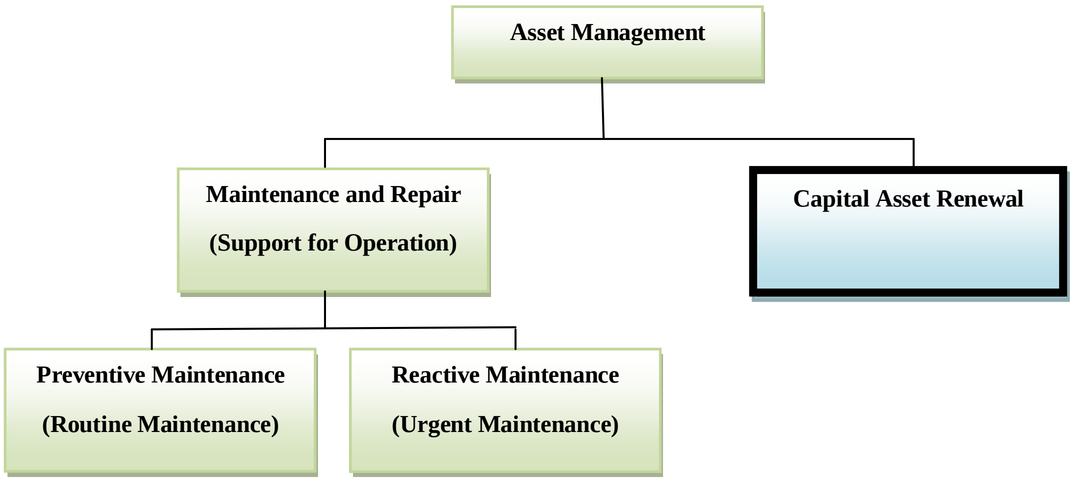


Figure 2.2: Asset management dimensions (Elhakeem and Hegazy 2010)

As summarized in Table 2.1, early definitions of asset management published in the literature were focused on its function as a structured decision support process and were not sufficiently comprehensive.

In more recent research, Brown and Humphrey (2005) provided a more generic and accurate definition of asset management, describing it as a balance of performance, cost, and risk: "Asset management is the art of balancing performance, cost and risk. Achieving this balance requires support from three pillars of competence: management, engineering and information." Alegre et al. (2006) later incorporated this definition into the general concept of sustainable asset management, which takes into consideration the various levels of decision making, as shown in Figure 2.3. Such a comprehensive view that links all concepts is important in the design of asset management systems for specific types of assets.

Table 2.1: Definitions of Asset Management

Definition	References
"A business process and decision-support *framework that: (1) covers the extended service life of an asset; (2) draws from engineering as well as economics; and (3) considers a diverse range of assets."*	(Vanier and Rahman 2004b)
"*Asset Management is a systematic approach of maintaining, upgrading, and operating physical assets cost effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning.*"	The Federal Highway Administration (FHWA, 1999)
"Asset Management is a comprehensive business strategy employing people, information and technology to effectively and efficiently allocate available funds amongst valued and competing asset needs."	The Transportation Association of Canada (TAC, 1999)
"Asset Management is a methodology to efficiently and equitably allocate resources amongst valid and competing goals and objectives	The American Public Works Association (APWA, 1998)
"[Asset Management is a] systematic process of maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public's expectations."	Organization of Economic Cooperation and Development (OECD), 2000

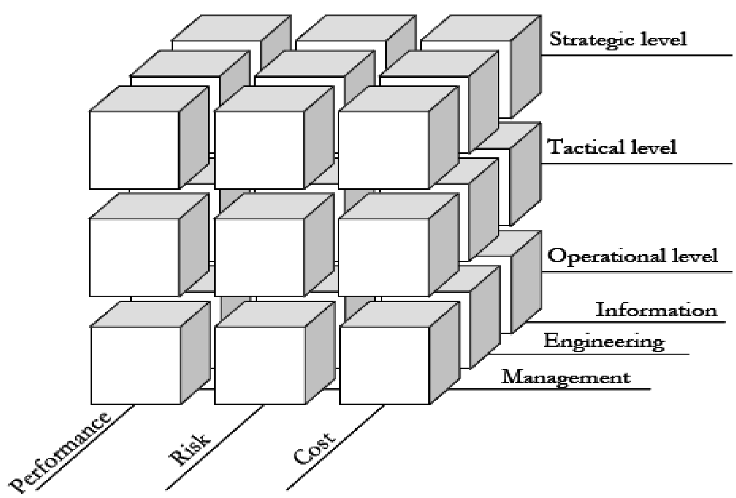


Figure 2.3: Sustainable asset management (Alegre 2006)

2.4 Asset Management Functions

Based on most recent definitions of asset management, typical asset management functions for capital renewal purposes can be grouped into five main categories, as shown in Figure 2.4 (Abdel-Monem and Ali 2010) and explained below.

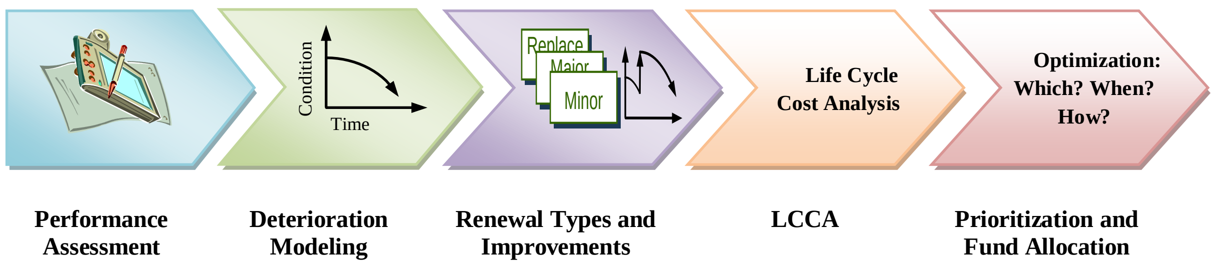


Figure 2.4: Main asset management functions for capital renewal

1. Performance Assessment: This function is the process of inspecting assets and assessing their condition indices, the extent of various defects, and their performance according to any desired performance criteria, such as sustainability, level of service (LOS), risk, green building standards, reliability, capacity, and future demand.

2. Deterioration Modeling: This function entails predicting the performance of the asset in subsequent years and developing a graph that shows the deterioration of the asset over time. Simple models assume linear deterioration with age. More detailed Markov chain models use condition data to estimate future deterioration.

3. Renewal Type Selection: This function involves choosing the appropriate renewal policy among the optional available methods of renewal (e.g., minor, medium, major or full

replacement). Each type includes estimates of the cost as a percentage of the asset replacement cost and the resultant improvement in performance.

4. Life Cycle Cost Analysis (LCCA): This study of the cost of the asset throughout its life cycle helps managers arrive at decisions that are best for both the short term and the long term and that can extend the lifespan of the asset.

5. Prioritization and Fund Allocation: This function ranks the assets according to performance priorities and distributes funds among these assets. Prioritization is based on a technique that ranks assets according to their performance index/condition/importance in order to facilitate decisions related to renewal type and fund allocation, whereas fund allocation is the allocation of available funds to assets based on decisions about the type and year of the renewal. A simple approach is to allocate funds according to the asset priority ranking; a better approach is to use an optimization technique designed to suggest the best decisions based on a framework that links decisions about renewal types and renewal timing to costs, performance, deterioration, and constraints. Optimization tools can help managers arrive at optimal decisions that maximize performance with minimal cost.

The next sections include details about asset management tools; background about the specific challenges associated with healthcare facilities, which are the focus of this research; and information about each type of asset management function.

2.5 Asset Management Tools

To support capital renewal decisions, existing asset management tools focus either on a specific type of asset (e.g., buildings) or on a specific type of component (e.g., only roofs). The engineered management systems (EMSs) implemented by the US Army Corps of Engineers, for example, handle individual asset types, e.g., PAVER (Shahin 1992), ROOFER (Bailey et al. 1989), BUILDER (Uzarski 2002, 2007), and VFA (2013). Other general-purpose systems, e.g., ReCAPP (PPTI 2006) and TOBUS (Brandt and Rasmussen 2002), are also available commercially. For hospital buildings, systems such as VFA.facilities (VFA 2013) and Archibus (FCI 2013) were also developed as specialized asset management systems. Such systems provide assistance for decisions related to inspection, asset prioritization, and fund allocation.

Despite their benefits, existing systems also entail a number of challenges with respect to performance evaluation and the prioritization of assets for renewal purposes (Halfawy et al. 2005). One of the primary problems with existing systems is the significant time and cost of the manual and subjective process required for the inspection, which necessitates work both on-site and in the office. Even when they incorporate the use of handheld devices, existing systems allow only text-data entry during inspection without location-based visual reference to problem areas. The other main drawback of existing systems is their reliance on the physical condition or another simple criterion alone as a means of prioritizing assets for capital renewal. In the hospital domain, for example, the Canadian Ministry of Health and Long-Term Care (MHLTC) uses a simple renewal-fund-allocation model that is a direct percentage of the hospital's operating funds in previous years (MHLTC 2008). This simple model fails to take into consideration important performance indicators such as the quality of hospital services, the availability of newer technology to improve services, patient demographics at the specific hospital location, energy-savings, environmental issues, and the business value retained and passed on to subsequent generations. Typically, little guidance is given to individual hospitals with respect to key performance indicators (KPIs) that support internal decisions about when and how to renew which components in order to avoid the risk of critical equipment failure and to increase the LOS satisfaction for all stakeholders, including patients and staff.

2.6 Healthcare Facilities

Healthcare facilities are among the most important civil infrastructure assets and include a wide range of types, from medical clinics to large and complex hospitals, as shown in Figure 2.5. These facilities are also considered among the most complex to manage, operate, and maintain (Lavy and Shohet 2009) but are also expected to provide efficient and effective service at all times.

In the United States (US), healthcare is a $2.8 trillion (17 % of the GDP) industry (Frampton et al. 2003), involving over 120,000 buildings. Due to the complexity of the electro-mechanical systems, the sophistication of the equipment (Shohet 2003a), and the significant differences among the functional areas within the buildings, all of which must be managed within a limited maintenance budget, management of the maintenance of hospital buildings is an enormous challenge.

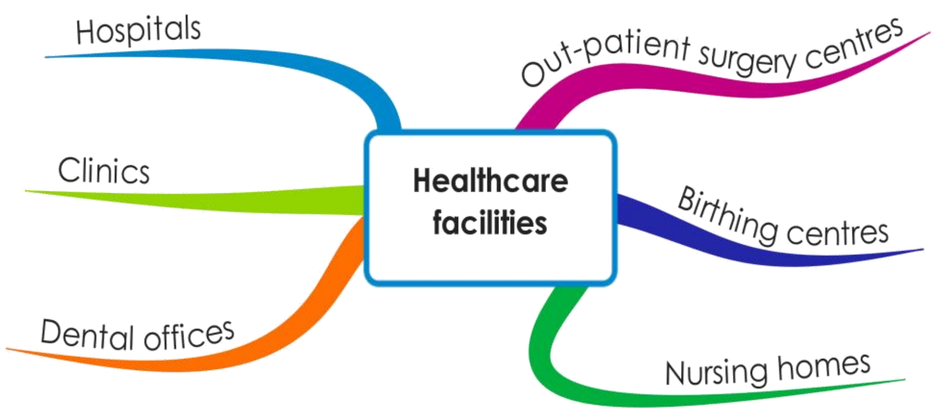


Figure 2.5: Types of healthcare facilities

2.7 Asset Management for Hospital Buildings

As highlighted in Figure 2.4**,** sustaining the safety and operability of a hospital building requires an asset renewal program that involves numerous functions: the accurate inspection and performance assessment of all subsystems; the prediction of future deterioration in the condition of these subsystems along a planning horizon (e.g., five years); the identification of renewal types and estimation of their costs and benefits in terms of condition improvement for each subsystem; and life cycle cost analysis in order to determine, given budgetary and other constraints, which subsystem must be renewed, which renewal types are the optimal choice, and when it would be best to renew these subsystems. The limited research related to healthcare facilities with respect to the five functions is discussed in the following sections.

2.8 Performance Assessment

The goal of performance assessment is to measure not only the physical condition but, more generally, the performance of each subsystem in a hospital building with respect to a variety of performance criteria. Extensive research has been carried out in a number of diverse directions that have been pursued mostly in isolation: the identification of the KPIs that should be used in multi-criteria evaluations, methods of physical condition evaluation, LOS evaluation, risk and reliability assessment, and sustainability assessment. Representative studies are discussed in the following subsections.

2.8.1 Identification of key performance indicators

KPIs are a set of metrics for measuring the performance of assets against organizational objectives. These indicators help decision makers measure and identify gaps between current and desired performance and also provide an indication of progress with respect to closing such gaps. KPIs are therefore crucial for enabling decision makers to improve their management of assets because carefully selected KPIs identify precisely where action should be taken in order to improve performance.

Based on the literature, many KPIs have been developed for hospital buildings: for example, in Greece at the Regional Healthcare Authority Level, Berler et al. (2005) identified 58 KPIs. These indicators were categorized according to four perspectives, as shown in Table 2.2, and were focused on the business environment of the hospital, without consideration of hospital renewals.

Table 2.2: Key performance indicators in a regional healthcare setting (Berler et al. 2005)

Perspective	No. of indicators	Performance Indicators List
Financial	14	Treatment cost, medical cost, drugs cost, laboratory, radiology, medical materials consumption, surgical procedure, department operational costs, vaccination, medical examination, return of capital employed, net cash flow, income per employee, payroll
Customer (Patient)	12	Mortality rate, morbidity rate, number of medical staff, number of beds, accessibility of patients to the medical units, time on waiting list, appointments per day, equity of delivered care, number of readmissions per patient, mean length of stay, patient satisfaction rate, number of cases with an electronic health record (EHR)
Processes	20	Length of stay, patient admission rate per medical unit, % of bed coverage, vaccination rate, tests performed per patient, number of inpatients, number of outpatients, number of drug prescriptions, number of laboratory tests, number of surgery procedures, number of radiology tests, number of visits in outpatient clinics, number of visits in primary care, number of dental care processes, number of emergency cases processed, number of unprocessed order entries, number of preventive care visits, number of home care monitored patients, number of inpatients from the outpatient clinic, number of medical procedures per day
Learning and Growth	12	Growth in usage of medical devices, training rate of healthcare professionals, employee satisfaction rate, number of doctors per bed, number of nurses per bed, ratio of existing healthcare professionals to expected job positions, personnel productivity rate, number of medical interventions per doctor, number of patients with re-examinations, admissions per case type, dismissals per case type
Total	58	

Shohet (2003a, 2003b) also developed KPIs for hospital buildings based on the statistical and quantitative analyses of 17 hospital buildings. His key indicator was the building performance indicator (BPI), which expresses the physical-functional condition of the building and is then used as part of a mathematical expression for calculating a maintenance efficiency indicator (MEI). Shohet (2003a, 2003b) considered ten building systems, as shown in Table 2.3, each having a relative weight (W_n) whose derivation is based on the relative life cycle cost of the system.

Table 2.3: Main building systems

Serial No.	System
1	Structure
2	Exterior Envelope
3	Interior Finishing
4	Electrical
5	Water and Waste Water
6	Heat, Ventilation, and Air Conditioning (HVAC)
7	Fire Protection
8	Elevators
9	Communications
10	Medical Gases

The performance (P_n) of each building system (n) is then evaluated according to three criteria: actual physical performance, frequency of failures in the system, and actual preventive maintenance carried out on the systems, as follows:

$\boldsymbol{P_n}$ (Score Performance) = $C_n * W_c + F_n * W_f + PM_n * W_{pm}$

where **(C_n)**: actual condition

(F_n): failures affecting the service provided by the system

(PM_n): actual preventive maintenance for the system

Wc: weight of the component condition of system n

W_f: weight of failures in system n

W_{pm}: weight of preventive maintenance for system n

The BPI is calculated as

$$BPI = \sum_{n=1}^{10} P_n \bullet W_n$$

A sample of the BPI results for 17 hospitals is shown in Table 2.4. Based on this study, it was found that the level of occupancy and age of the building are two significant factors that influence building performance and that must be included in deciding the budget for renewal operations. Another important constraint is that a minimum BPI for a hospital building and its systems is 70.

Table 2.4: Building performance indicator - field survey of 17 hospital buildings (Shohet 2003a)

Serial No.	BPI	Structure	Exterior envelope	Interior finishing	Electrical system	Water and waste water	HVAC	Fire protection	Elevators	Communications	Medical gases
1	80.4	94.0	88.3	86.0	83.3	72.9	60.0	75.0	61.4	41.7	100.0
2	78.3	68.5	71.0	80.2	91.7	79.2	70.0	75.0	87.1	41.7	100.0
3	74.1	90.0	79.3	77.3	58.3	58.3	65.0	100.0	74.3	58.3	100.0
4	74.1	90.0	95.8	70.0	58.3	85.4	62.5	75.0	87.1	58.3	100.0
5	72.6	72.0	35.3	74.6	91.7	58.3	66.7	75.0	74.3	*	100.0
6	71.4	82.0	79.3	77.3	58.3	70.8	52.5	75.0	74.3	41.7	100.0
7	69.4	67.5	53.0	77.7	58.3	66.7	62.5	75.0	82.9	25.0	100.0
8	67.4	78.0	54.5	56.1	83.3	60.4	72.5	100.0	70.0	25.0	100.0
9	67.2	68.5	54.5	59.0	91.7	58.3	72.5	75.0	57.1	41.7	100.0
10	66.1	72.0	67.7	56.1	66.7	79.2	65.0	100.0	82.9	25.0	100.0
11	66.1	60.0	62.0	55.4	91.7	58.3	71.7	75.0	70.0	*	100.0
12	65.4	72.0	63.1	54.7	91.7	52.1	60.0	100.0	70.0	33.3	100.0
13	64.7	84.0	62.0	53.3	58.3	75.0	67.5	75.0	78.6	41.7	100.0
14	64.7	78.0	63.5	56.1	58.3	70.8	70.0	75.0	70.0	41.7	100.0
15	63.7	66.0	59.3	50.5	91.7	58.3	57.5	100.0	74.3	*	100.0
16	63.3	72.0	82.7	56.1	66.7	60.4	58.1	100.0	48.6	41.7	100.0
17	62.0	66.0	33.8	47.7	91.7	58.3	67.5	75.0	82.9	33.3	100.0
Mean	68.9	75.3	65.0	64.0	76.0	66.1	64.8	83.8	73.3	39.3	100.0

* Not available.

2.8.2 Physical condition evaluation

The goal of the condition assessment process is the evaluation of the current physical condition of a building's subsystems and services by an expert assessor. The results of the condition assessment are needed for a number of asset management functions, such as deterioration modeling or the selection of repair type, and ultimately for the development of appropriate renewal policies.

Field inspection and data gathering are methods required for collecting the data necessary for an assessment of the condition of an asset: type, intensity, and extent of distresses. The inspection should be consistent, accurate, and as objective as possible; many techniques can be employed that rely on a variety of methods, including visual inspection, photographic and optical methods, non-destructive evaluation methods, and smart sensors (Hudson et al. 1997). Of these methods, visual inspection can be considered the most suitable approach for the majority of building components (Elhakeem and Hegazy 2010).

A visual assessment of physical condition can be conducted using one of two methods:

1. The distress survey method is the more accurate approach and is also reproducible (Uzarski 2002). It is based on categorization according to a number of generic distress types that relate to building components (e.g., broken, leaking, disfunctional) and is usually employed for identifying the reason for the failure.
2. Direct condition rating is a less accurate but faster method of performing a condition survey. Each component is inspected visually and evaluated against a set of criteria (Uzarski 2002), as good, fair, poor, or critical. This method is more practical if the purpose of the assessment

is related to decisions about renewal; it was therefore chosen for this research as a means of evaluating the physical condition of a building's subsystems.

Sample condition rating scales used for rating the condition of a subsystem are shown in Table 2.5. The visual condition rating scale for building subsystems ranges from 0 to 100, where 0 represents a critical condition, and 100 represents a new condition.

Table 2.5: Condition rating scales and linguistic representations

Asset type	Condition scale	Linguistic representation	Reference
Buildings	0-100	(0-20)=No deterioration; (20-40)=Slight deterioration; (40-60)=Moderate deterioration; (60-80)=Severe deterioration; and (80-100)=Critical deterioration	Elhakeem and Hegazy (2005a)
Buildings	0-100	(0-10)=Failed; (10-25)=V. Poor; (25-40)=Poor; (40-55)=Fair; (55-70)=Good; (70-85)=V. Good; and (85-100)=Excellent	Uzarski and Burley (1997)
Buildings	1-6	1=Excellent; 2=Good; 3=Fair; 4=Poor; 5=Bad; and 6=V. Bad	Straub (2009)

2.8.3 Level-of-service evaluation

Inadequate and/or poor infrastructure levels of service (LOS) ultimately reduce the user's satisfaction and the community's quality of life and compromise the health and safety of its citizens (Sharma et al. 2008). The LOS is an index that indicates the quality, quantity, capacity, and reliability of the service provided by the asset and helps in decision making related to the development, operation, maintenance, rehabilitation, planning, and renewal of municipal infrastructure assets (Infrastructure Canada 2002). The LOS is commonly used in the assessment of transportation (Sharma et al. 2008) and buildings (Arkin and Paciuk 1997). For example, Sharma et al. (2008) proposed asset levels of service (ALOS) for a road in an urban municipality as a means of combining LOS indices for vehicle users, bicyclists, and pedestrians. The methodology for the determination of the ALOS is shown in Figure 2.6.

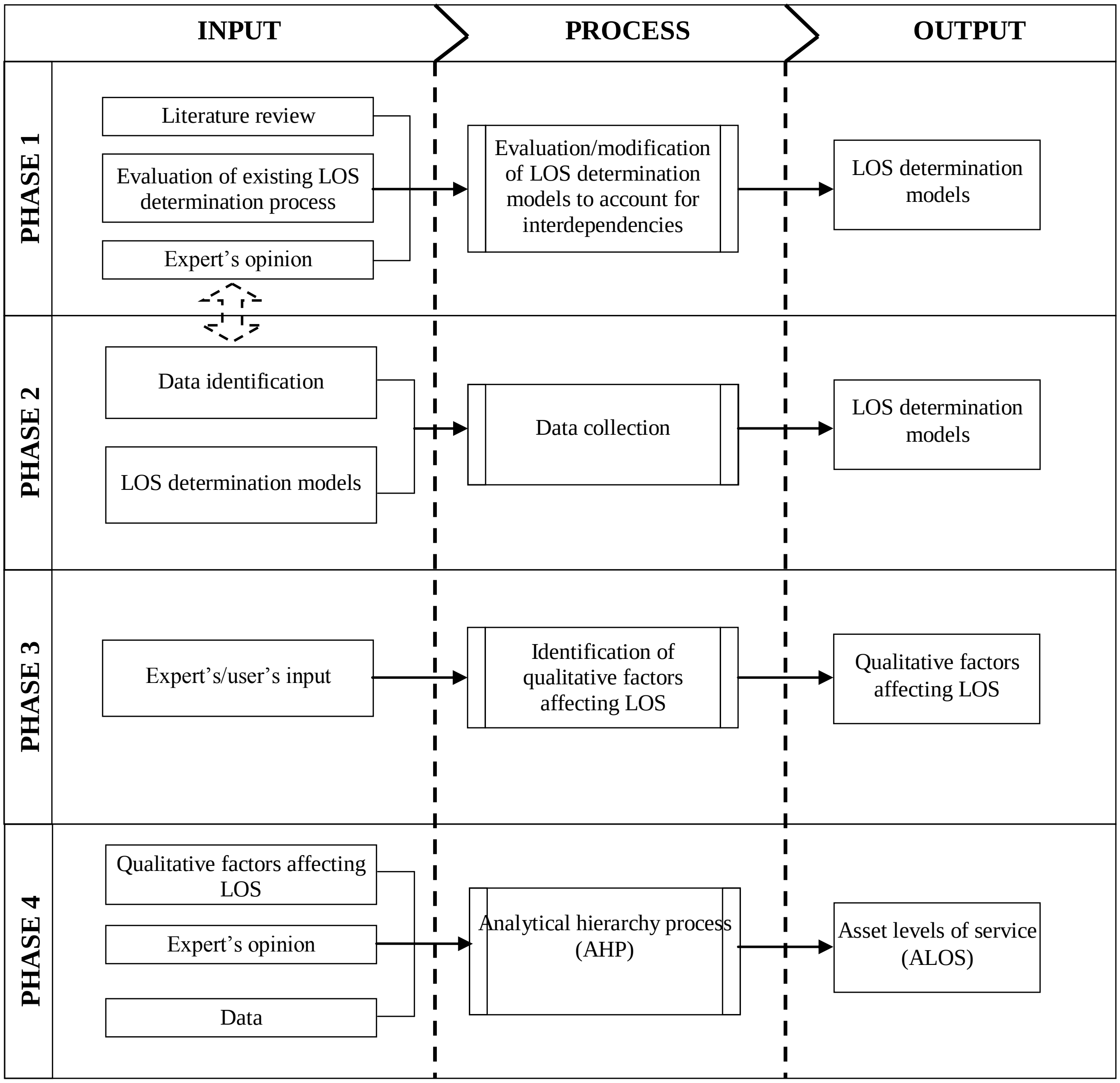


Figure 2.6: Methodology for the determination of the ALOS (Sharma et al. 2008)

The primary challenge in evaluating the ALOS for any asset is the interdependence of its various users and their differing needs. Existing mathematical ALOS quantification models are therefore combined with techniques such as the analytical hierarchy process (AHP) in order to quantify the ALOS. The AHP method breaks down complex problems into specific components, arranges these components into a hierarchy, and assigns numerical values based on subjective judgments of the relative importance of each variable. The cumulative priorities of each variable are then calculated (Saaty 2004). This method has been widely used as a means of quantifying intangible factors (Saaty 2008; Sharma et al. 2008). Details of the AHP can be found in the literature (Saaty 2004, 2008).

The research presented in this thesis has led to the development of an indicator that measures the LOS for hospital users (medical staff, maintenance staff, patients, and visitors). The subsystems and services whose evaluation is necessary for a determination of the LOS were identified through surveys and/or an interview with the specialist at the hospital under study.

2.8.4 Risk and reliability assessment

A risk assessment must be in place in every hospital and should be high priority for all healthcare facilities (O'Donovan 1997). A risk assessment integrates reliability with safety and environmental issues and can therefore be used as a decision tool for renewal planning in order to minimize the probability and consequences of system failure with respect to safety as well as economic and environment factors (Khan and Haddara 2003).

In general, risk assessment can be either quantitative or qualitative. The result of a quantitative risk assessment is a number, such as cost impact ($) per unit of time, and this number could be used as a means of prioritizing a series of items that have been risk assessed. Quantitative risk assessment also requires a great deal of data both for the assessment of probabilities and the assessment of consequences. The results are often shown in the form of a simple risk matrix, in which one axis represents probability and the other represents consequences. A qualitative risk value is a relative number that has little meaning outside the framework of the matrix (Khan and Haddara 2003).

Khan and Haddara (2003) proposed a risk-based maintenance (RBM) framework (Figure 2.7) for reducing the overall risk of failure of the operating facilities. The framework is comprised of three main modules: a risk estimation module, a risk evaluation module, and a maintenance planning module. Details of the three modules are provided in their report.

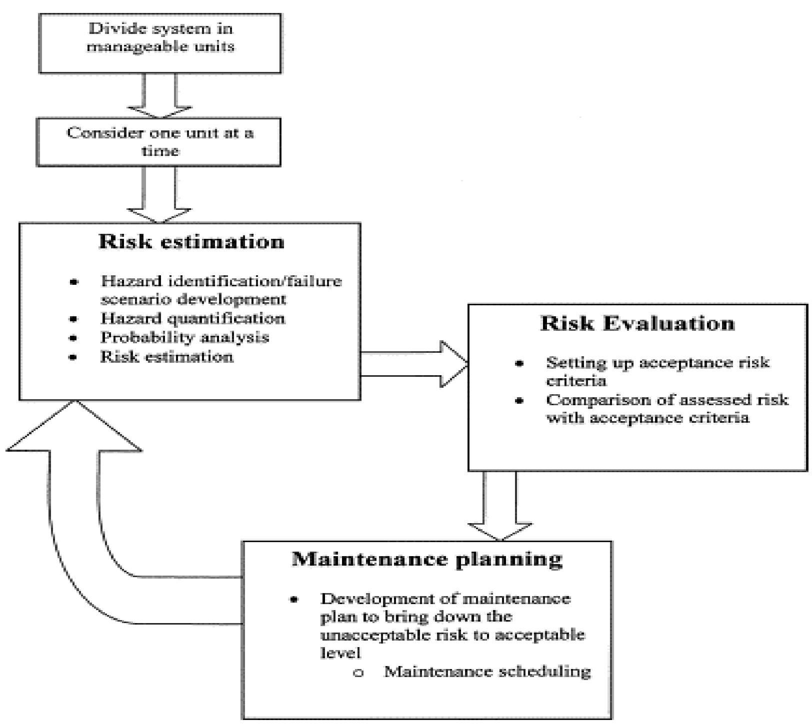


Figure 2.7: Architecture of a risk-based maintenance methodology (Khan and Haddara 2003)

The evaluation of the consequences of the failure of critical systems, such as HVAC, medical gases, fire protection, or electrical systems, may lead to both casualties and financial losses (Shohet and Lavy 2004). A performance indicator for risk is therefore needed in order to help management make optimal cost-effective decisions concerning investments in capital renewal. For the research presented in this thesis, the data required for calculating this indicator were collected from the maintenance department at each hospital under study.

2.8.5 Sustainability assessment

A sustainability assessment is based on six main categories: sustainability of the site, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality (IEQ), and innovation and design (Green Building and LEED Core Concepts Guide 2009). Lützkendorf and Lorenz (2005) introduced nine requirements for sustainable buildings, as shown in Table 2.6.

Table 2.6: Sustainable building requirements

Aspects	Requirements
Economic, environmental, and social	Minimization of life cycle costs, reduction of land use, reduction of raw materials, avoidance/reduction of hazardous substances, reduction of CO_2 emissions and other pollutants, reduction of impact on the environment, protection of health and comfort of building occupants/users as well as of neighbours, preservation of building's cultural value.
Users' and occupants' needs	Maximization of the building's serviceability and functionality

Wilson et al. (1998); Heerwagen 2000; Yates (2001); and Lützkendorf and Bachofner (2002) also pointed out that sustainable buildings are more cost-efficient, effective, profitable, and marketable.

Kumar and Fisk (2002) and Heerwagen (2002) identified strong correlations between sustainable design features (e.g., natural lighting, thermal comfort, air quality, worker-controlled temperature and ventilation) and reduced symptoms of illness, decreased absenteeism, and significantly increased measured workforce productivity. In addition to maintaining a healthy environment for the occupants, a hospital building should be one of the most sustainable buildings because of its high consumption of energy and water, and because of the large amounts of waste it produces.

Existing KPIs for hospital buildings generally focus on the physical condition of the building, targeting only business and operational issues, with all of these indicators being used for prioritizing renewal activities rather than for optimization. Additional performance indicators are therefore needed (Shohet 2003a) if decision makers in healthcare facilities are to be able to assess and improve the performance of their facilities when they make renewal decisions. Such KPIs can also be used for setting optimum fund allocations for renewal policies, which was one of the goals of this research. The next sections describe other considerations that should be included in an effective decision support system for hospitals.

2.9 Deterioration Modeling

Due to factors such as wear and tear, severe environmental conditions, user misuse or abuse, and deferred maintenance decisions, the deterioration of a building begins the moment it is constructed (Douglas 1996). The deterioration patterns of building components are not identical: some deteriorate linearly and others non-linearly (Shohet et al. 2002; Shohet and Paciuk 2004). As shown in Figure 2.8, deterioration patterns for a building component are categorized as one of two main types: deterministic or stochastic. These models are essential for predicting the future condition of building components (Madanat 1993; Madanat et al. 1997; Morcous et al. 2002a; Elhakeem and Hegazy 2005b), and the reliability of such models depends largely on the quantity and quality of the historical condition data available.

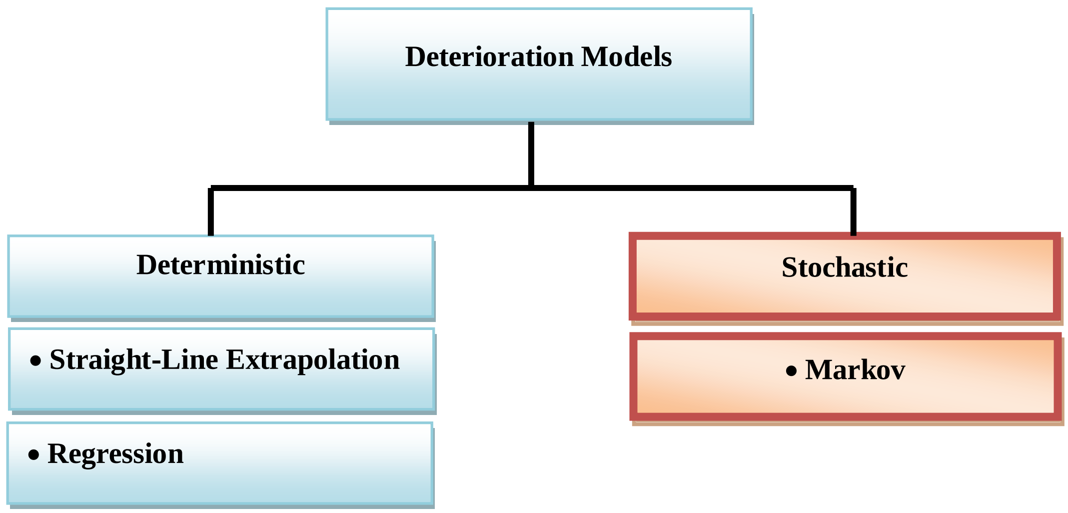


Figure 2.8: Deterioration models

2.9.1 Deterministic models

Deterministic models are based on the assumptions that building components deteriorate at a deterministic rate, i.e., that no probabilities are involved and that the output of such models is a set of deterministic values that are dependent on a mathematical or statistical formula that expresses the relationships between the variables. This type of model includes a variety of methods, such as straight-line extrapolation, and regression models (Elhakeem 2005; Morcous 2002a, 2002b). Each method is explained briefly below.

Straight-line extrapolation: As shown in Figure 2.9, this method requires only two known conditions in the history of the asset, for example, the initial condition of the asset and any condition measurement carried out after construction. The model can be established by linking these two points so that the condition at any time in the future can be extrapolated. This method is thus a simple means of predicting the future condition of building components, and because of this simplicity, it was used in this research.

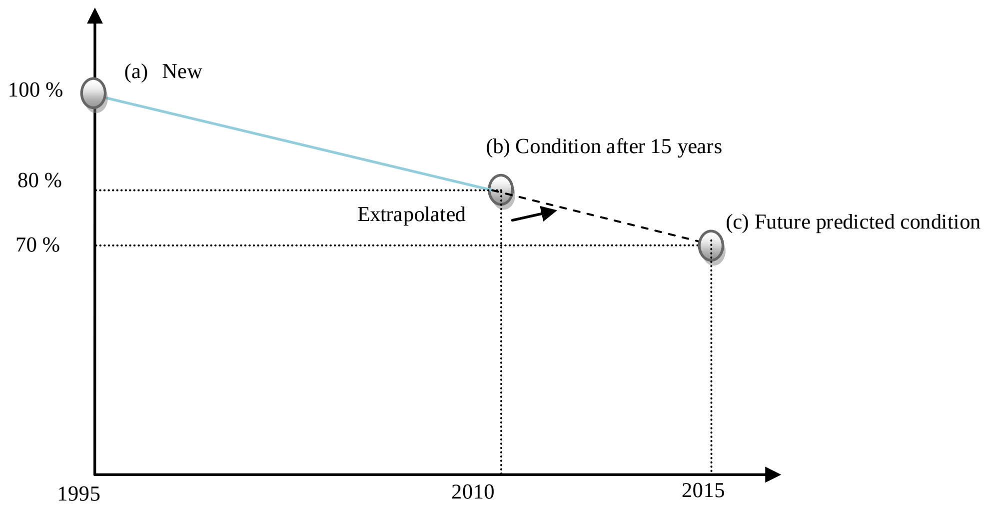


Figure 2.9: Straight-line extrapolation

Regression: This method is more accurate than the simple straight-line extrapolation. A regression model is used as a means of establishing an empirical relationship between two or more variables: one dependent and one or more independent (Elbehairy 2007). Each variable is described in terms of its mean and variance (Shahin 1994). Several forms of regression models, both linear and non-linear, have been presented in the literature.

2.9.2 Stochastic Model

A stochastic model expresses the deterioration of building components in terms of the likelihood that the component will be in a given condition, thus accounting for uncertainties such as those related to the impact of environmental factors. The application of such models is now being increasingly used in engineering and other science fields (Elbehairy 2007). The technique most commonly used for predicting infrastructure asset deterioration is the Markov chain model (Flintsch and Chen 2004; Elhakeem and Hegazy 2005b):

$$[FP_t]_{1xn} = [IP_0]_{1xn} \,.\, [TPM]^t{}_{nxn}$$

where $[FP_t]_{1xn}$ is the future-state vector of an asset after any time interval t; $[IP_0]_{1xn}$ is the initial probability vector; and $[TPM]^t{}_{nxn}$ is a transition probability matrix, where n is the number of possible condition states.

The Markov model predicts the deterioration of a component by defining discrete condition states and accumulating the probability of a transition from one condition state to another over multiple discrete time intervals (Lounis et al. 1998; Elhakeem and Hegazy 2005b). This model requires historical data (Elhakeem and Hegazy 2005b) and is used by many state-of-the-art infrastructure management systems, such as Pontis, BRIDGIT, and MicroPAVER, because of its ability to predict the performance of infrastructure facilities. It is also widely used for determining the optimal maintenance and renewal decision policy in situations that involve uncertainties (Farran and Zayed 2009).

2.10 Renewal Type Selection

The selection of renewal type refers to the determination of suitable renewal options along with an estimate of the impact on the condition. The cost of a renewal generally depends on the type of renewal and is usually assigned as a fixed percentage of the replacement cost of the component (Seo, 1994). For example, light, medium, and extensive types of renewal for bridge decks were estimated by Seo (1994) to cost 28.5 %, 65 %, and 100 % of the replacement cost, respectively. The effect of each type of renewal on the condition of the components can be represented as shown in Figure 2.10, and the deterioration behaviour of the component after the renewal is very important. Researchers commonly assume that the deterioration trend after the renewal is parallel to the deterioration trend prior to the renewal, as shown in Figure 2.11 (Seo 1994; Hegazy et al. 2004; Langevine et al. 2005; Elhakkem 2005).

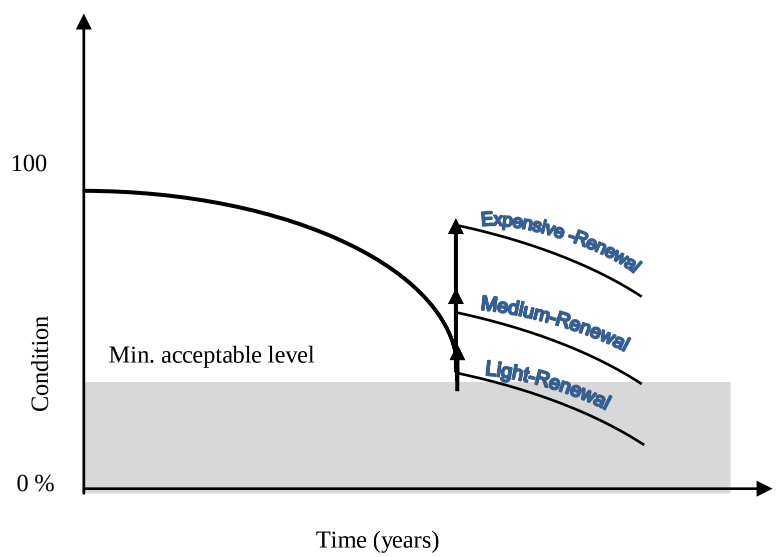


Figure 2.10: Effect of the renewal type on component performance

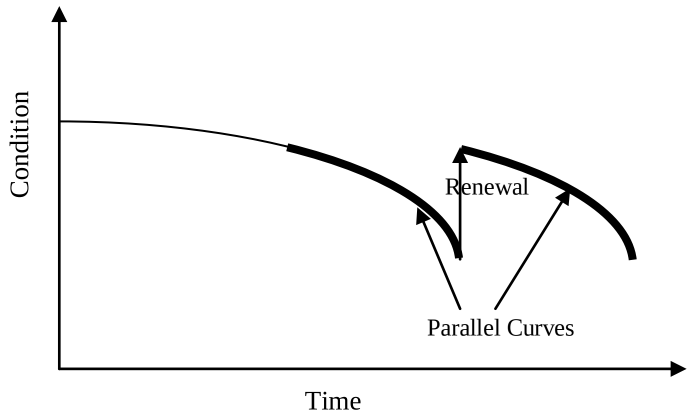


Figure 2.11: After-renewal deterioration

As mentioned, a hospital building contains a variety of systems within its main functional zones, and each system includes diverse subsystems that differ with respect to their significance and criticality. Each of these subsystems has a different rate and pattern of deterioration over time, and each requires specific renewal interventions for its performance to be improved, emergency renewal work to be reduced or eliminated, and risks and costs to be decreased. Renewal planning therefore requires knowledge of the physical condition of the building subsystems, the importance of each subsystem, and possible renewal options, all of which are useful for building managers when they are estimating and allocating renewal budgets.

2.11 Life Cycle Cost Analysis

Life-cycle cost analysis (LCCA) is a decision-making approach that is used as a means of evaluating the total cost accrued over the entire life of an infrastructure facility from its construction to its replacement or final demolition (Morcous and Lounis 2005). It incorporates initial and discounted future costs over the life cycle of the alternative investments and is employed as a method of identifying the best value or the lowest cost over time (Haas et al. 2003, 2004). LCCA has always been an important tool for supporting decisions with respect to the determination of the most cost-effective decisions for assets such as roads, utilities, or buildings or for selecting the most effective renewal treatment.

An extension of earlier work related to educational buildings, the research presented in this thesis integrates renewal decisions for healthcare facilities, taking into consideration the important KPIs (physical condition, level of service, risk, and sustainability) for setting a renewal plan.

2.12 Prioritization and Fund Allocation

One of the primary challenges facing asset managers is the process of allocating available funds in order to maintain asset conditions within satisfactory levels or to maximize the benefits of expenditures (Al-Battaineh et al. 2005). In an ideal situation of unlimited funds, all renewals needed for all components can be addressed (Hudson et al. 1997). However, in most public infrastructure organizations, renewal funds are limited so that the prioritization of building subsystems for renewal purposes becomes crucial, and decisions regarding the subsystems to be renewed, the appropriate renewal strategies, and the timing of the renewal must be decided realistically and efficiently.

In general, subsystem prioritization refers to a sequential order of the subsystems based on their importance in order to allocate the available funds to cover maintenance costs for these subsystems. This process is complex, particularly when hundreds of subsystems are involved. The demand for research into maintenance prioritization methods is therefore increasing because today’s maintenance budgets do not meet maintenance requirements (Shen 1997).

The process of subsystem prioritization can be accomplished using a variety of methods, ranging from simple subjective ranking to more accurate optimization, in which all possible combinations of "which, what, and when" are evaluated with respect to an objective function (Hudson et al. 1997; Elhakeem 2005). Samples of current practices used by a variety of organizations for setting maintenance prioritization are shown in Table 2.7.

Table 2.7: Current practices for setting maintenance prioritization

Type of Building	Description of Priority Criteria	Reference
Hospitals	Physical Condition, Performance, and Preventive Maintenance	(Shohet 2003a &b)
	Hong Kong Hospital Authority The principles of priority criteria applied are 1-Health and safety; 2-Risk to patients; 3-Statutory requirements; 4-Risk to clinical services; 5-Environmental issues; 6-Urgent repair; 7-Preventive maintenance; 8-Routine maintenance; 9-Major maintenance; 10-Capital renewal; 11-Barrier free access; and 12-Appearance.	(Chan 2003)
	Ministry of Health and Long-Term Care – CANADA The grant must first be used for critical or highest priority projects. These projects include those required to address 1-Requirements under the Occupational Health and Safety Act; 2-Requirements under the Ontario Building Code and Ontario Fire Code; 3-Other facility-related legislative requirements; or 4-Potential interruptions in the operation of a facility. After completing the highest-priority projects, the HIRF grant can be used for projects of a lesser priority, such as projects that 1-Are intended to improve the efficiency of building systems (i.e., energy efficiency); 2-Are deemed necessary to reduce or minimize the downtime of building systems resulting from predictable building deterioration; and 3-Address accessibility issues (e.g., installing ramps to provide access for people with disabilities, renovating washrooms to provide barrier-free access, etc.).	(MHLTC 2008)
Schools	Department of Education and Science in the UK. 1-Work needed immediately or in the near future to meet legislative requirements and to ensure the health and safety of building occupants and users; work required to prevent the imminent closure of accommodation or serious dislocation of activities. 2- Work necessary within one year to prevent serious deterioration of the fabric or services, such as those which are likely to lead to higher future costs of repair or renewal. 3- Work as above which many be deferred beyond one year; work desirable to maintain the environmental quality of buildings and grounds, such as internal decorations, fencing, etc.	(Shen 1997).

Table 2.7 (count.)

Universities	Universities in Taiwan 1- Use necessity; 2- Maintenance urgency; 3-Impact on individuals; 4-Impact on the public; 5-Current age relative to age/design limit; 6-Exterior condition; 7-Deterioration of components; 8-Functional impairment of main structure; 9-Functional impairment of walls and finish; 10-Functional impairment of electrical, air conditioning, communication, and monitoring/control; 11-Functional impairment of plumbing, sanitation facilities, and fire protection; 12-Value improvement rate; 13-Maintenance management efficiency; 14-Use efficiency	(Chang et al. 2008)
Housing	Hong Kong Housing Department Condition, Appraisal, Repair, and Evaluation (CARE) programme is as follows: 1- Work necessary to maintain the safety or persons; 2- Work necessary to keep property habitable, e.g., by reasons of hygiene, security, electrical, and water supply; 3- Work necessary to keep buildings operational; and 4- Work necessary for the appearance of the property and the provision or upkeep of non-essential services or facilities.	(Shen 1997)
Buildings	Building Maintenance Managers in Country Authorities - Technical factors, political factors, financial factors, social factors, economic factors, and legal factors	(Spedding et al. 1995)

When the process of allocating funds for the purpose of maintaining building subsystems is based on setting priorities for these subsystems, it does not generally lead to the optimal allocation of available funds so that the different types of renewals for each subsystem are taken into account. For the achievement of such an optimal allocation of the available funds among the subsystems that need to be renewed, a maintenance optimization concept produces effective results. Such a concept represents an attempt to balance the maintenance requirements (legislative, economic, technical, etc.) and the resources used to carry out the maintenance program (people, spare parts, consumables, equipment, facilities, etc.). The use of a maintenance optimization process also has the goal of selecting the appropriate maintenance technique for each subsystem within the building's systems and identifying the maintenance technique that meets regulatory requirements and maintenance targets with respect to safety, equipment reliability, system availability, and costs. Effectively implemented maintenance optimization improves system availability, reduces overall maintenance costs, increases equipment reliability, and enhances system safety.

The majority of the models reported in the literature that are developed for optimum fund allocations are based on the total LCC (Hegahzy et al. 2004; Elhakeem 2005) because the primary advantage of the LCC is the fact that decisions take into consideration the benefit gained along the whole planning horizon when the LCC is minimized. These models also use optimization tools such as genetic algorithms (GAs), which have been applied successfully in order to optimize complex combinatorial problems in a number of areas in civil engineering and construction, as shown in Table 2.8 (Flintsch and Chen 2004).

Table 2.8: Summary of soft computing applications in infrastructure management (Flintsch and Chen 2004)

Soft Computing Technique	Asset performance		Needs analysis		Tradeoffs analysis		Reference
	Condition Assessment	Performance Prediction	Project Selection	Treatment Selection	Prioritization Schemes	Optimization Techniques	
Artificial Neural Networks	**11**	**8**	**1**	**2**	**1**	**1**	Pant et al. (1993), Kaseko and Ritchie (1993), Hajek and Hurdal (1993), Fwa and Chan (1993), Eldin and Senouci (1995), Flintsch et al. (1996), Razaqpur et al. (1996), Cattan and Mohammadi (1997), Huang and Moore (1997), Alsugair and Al-Qudrah (1998), La Torre et al. (1998), Owusu-Ababia (1998), Shekharan (1998), Wang et al. (1998), Van der Gryp et al. (1998), Martinelli and Shoukry (2000), Lou et al. (2001), Farias et al. (2003), Felker et al. (2003), Fontul et al. (2003), Lee and Lee (2004), Lin et al. (2003), Sadek et al. (2003), Yang et al. (2003)
Fuzzy Logic Systems	**7**	**1**	**1**	**1**	**1**	**2**	Elton and Juang (1988), Zhang et al. (1993), Grivas and Shen (1995), Prechaverakul and Hadipriono (1995), Shoukry et al. (1997), Wang and Liu (1997), Fwa and Shanmugam (1998), Cheng et al. (1999), Saitoh and Fukuda (2000), Bandara and Gunaratne (2001)
Genetic Algorithms		**2**			**1**	**6**	Fwa et al. (1996), Liu et al. (1997), Pilson et al. (1999), Shekharan (2000), Miyamoto et al. (2000), Chan et al. (2001), Hedfi and Stephanos (2001), Ferreira et al. (2002)
Other Hybrid Systems	**6**	**1**		**2**			Ritchie et al. (1991), Chou et al. (1995), Taha and Hanna (1995), Martinelli et al. (1995), Abdelrahim and George (2000), Chiang et al. (2000), Chae and Abraham (2001), Liang et al. (2001), Flintsch (2002)
Total	**24**	**12**	**2**	**5**	**3**	**9**	

Numbers represent scholars who used the specific technique

The use of a GA technique thus has the potential to provide effective asset management optimization and was used in this research as a means of determining the most cost-effective decision.

2.13 Conclusions

This chapter has provided a review of the general condition of civil infrastructure assets in the US and Canada, the main functions of asset management, healthcare facilities and their importance, previous research with respect to KPIs for healthcare buildings, and the capabilities of available decision support tools.

The literature shows that the KPIs available for healthcare facilities focus only on business and the physical condition of the asset and not on other indicators such as LOS, sustainability, and risk. The majority of the available decision support systems also concentrate primarily on supporting day-to-day management activities, and only an extremely small number offer limited support for long-term renewal planning. As well, many fundamental asset management functions, such as performance modeling and renewal prioritization, are not supported by the majority of these systems.

The main difficulties associated with the prioritization of the renewal of building capital are the large number of components, the large number of renewal alternatives for each system in each year on the planning horizon, and budget limitations. The literature reports the use and testing of artificial intelligent (AI) techniques for the prioritization of renewals to bridges, buildings, and water pipelines. These techniques have also been used for the determination of the optimum fund allocation for the capital renewal of healthcare assets.

Chapter 3

Performance Assessment and Prioritization Framework

3.1 Introduction

This chapter presents a hybrid performance assessment and prioritization framework that incorporates three main functions for appropriately prioritizing the subsystems in a hospital building with respect to renewal actions: a two-dimensional hospital hierarchy, four key performance indicators (KPIs), and a visual inspection application. The formulations for determining the overall priority index for each subsystem based on these main functions are also introduced, along with details of the proposed framework and the formulations for identifying the overall subsystem importance (OSI), the overall subsystem deficiency (OSD), the overall subsystem priority index (OSPI), and the overall building performance index (OBPI).

3.2 Hospital Systems and Functional Zones

From a maintenance perspective, Shohet (2003a) divided a hospital into ten systems: structure; interior finishing; exterior envelope; fire protection; water and waste water; elevators; electrical systems; communications; heat, ventilation, and air conditioning (HVAC); and medical gases. From an architectural perspective, however, a hospital building can be divided into three functional zones, as suggested by James and Noakes (1994): clinical, nursing, and support. Each functional zone includes a group of spaces that share similar functional characteristics, as shown in Figure 3.1.

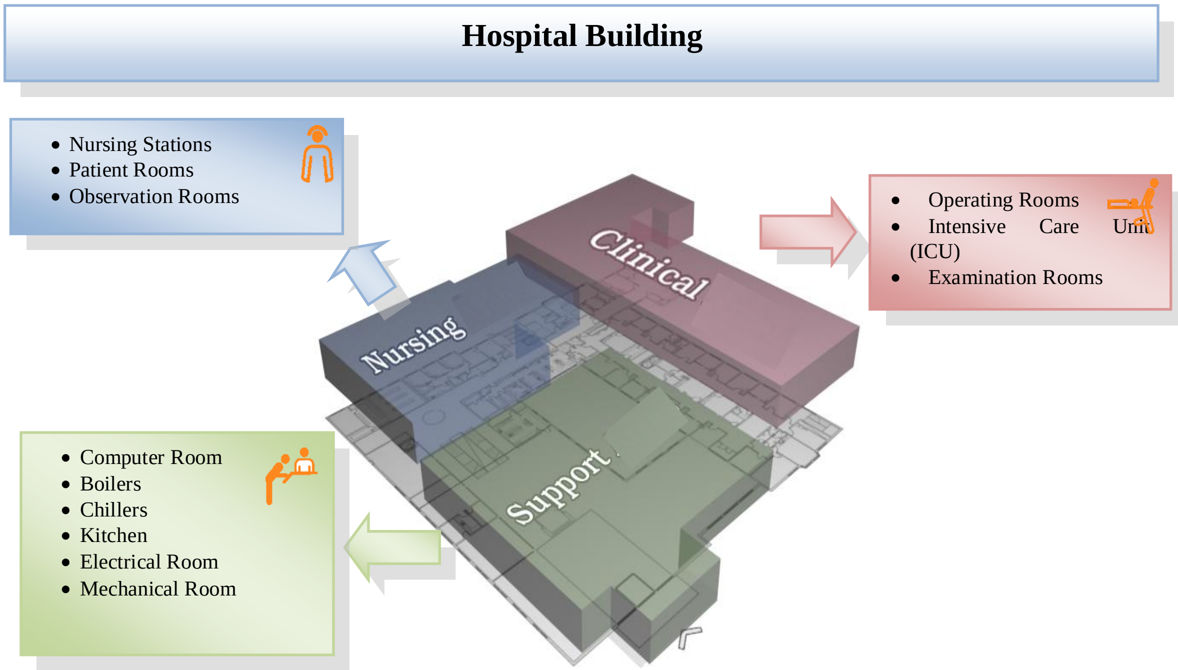


Figure 3.1: Main functional zones in a hospital building (based on James and Noakes 1994)

Because of the importance of spaces in buildings, recent research (Eweda et al. 2010) has presented a condition assessment model that considers space as the principle element to be evaluated. Their model therefore evaluates all of the systems within each space and then accumulates the information for all of the physical systems of the building. However, indiscriminately assessing all of the spaces in a complex building is both costly and time consuming. As well, consideration of condition as the only performance indicator is inappropriate for hospital buildings, in which enormous challenges are associated with the complexity of the electro-mechanical equipment (Shohet 2003a) and the significant differences among the functional spaces within the buildings.

A need thus exists for a faster inspection mechanism and a structured performance assessment approach that integrates physical condition with other important KPIs such as the level of service (LOS) observed at various spaces, sustainability considerations, and the risk of service failure. As reported in the literature, a number of researchers have examined some of these aspects individually: multiple-criteria performance analysis (Shohet 2006; Shohet and Lavy 2004); LOS attained from the perspective of multiple stakeholders (Nasser 2007); risk/reliability analysis (Christodoulou et al. 2009; Moubray 1997); social, economic, and environmental sustainability (Lützkendorf and Lorenz 2005); and the indoor environment quality (IEQ) of the building space (Eweda et al. 2010). The hybrid performance assessment framework discussed in this chapter was developed as a means of addressing the complexity of healthcare facilities. The framework incorporates multiple KPIs (condition, LOS, sustainability, and risk); assesses the impact of IEQ on the LOS provided by the systems; and appropriately prioritizes the systems for renewal action.

To better prioritize capital renewal work, building systems are assigned different levels of importance within each zone. For example, an interruption in the electricity in an operating room (within the clinical area) is more critical than lack of water because of the more serious consequences. Since chemicals and alternative products can be used to clean patients and equipment, the water supply is not considered as vital as the power supply, which is essential for maintaining the operation of ventilators and other equipment (Arboleda et al. 2007). Consideration of the nature of hospital buildings is therefore important in the design of an effective assessment framework so that capital renewal plans can be determined in a manner that minimizes risk and also improves the overall functionality of the hospital at minimal cost.

3.3 Development of the Framework

The developed framework for performance assessment, prioritization, and capital renewal optimization has been designed to incorporate five main functions, as shown in Figure 3.2 (Ali and

Hegazy 2013b): a two-dimensional hierarchy of hospital systems/spaces, multi-criteria performance assessment, visual all-on-site inspection, a prioritization mechanism, and capital renewal optimization. The first four elements relate to performance assessment and to the generation of an appropriately prioritized list of subsystems for capital renewal purposes. These functions have been designed based on input from hospital maintenance professionals obtained through a survey, as discussed in subsequent sections. A key consideration included in the design of the proposed framework is the necessity to account for the distinctive aspects related specifically to hospitals, including the diverse zones/spaces and their varying relative importance, specialized hospital equipment, and the varying types of assessment that provide reliable performance evaluation. The details of the first four framework functions are discussed in the following subsections, and the optimization function is explained in Chapter 6.

3.3.1 Two-dimensional hierarchy of systems and spaces

Hospital buildings normally encompass a number of interrelated physical systems, diverse functional spaces (e.g., operating rooms, patient wards, labs), and special systems (e.g., medical gas systems, nurse call systems) that represent important interdependent entities. For example, the quality of the physical systems has a significant effect on the quality of the indoor environment (e.g., temperature, lighting, and sound) inside the functional spaces (Eweda et al. 2010), which, in turn, directly impacts both patients and staff. Sustaining the operability of and a beneficial work environment in hospitals therefore requires the appropriate performance assessment of hospital systems and space so that capital renewal actions can be effectively prioritized.

To facilitate the accurate, speedy, and structured performance assessment of hospitals, the developed methodology defines a detailed hospital hierarchy and introduces three unique features that are critical for hospitals, as shown in step 1 in Figure 3.2: (i) identification of two hospital hierarchies, one for systems and subsystems, and the other for important zones/spaces; (ii) a special focus on key hospital equipment; and (iii) particular attention to hospital subsystems that provide shared services to multiple zones.

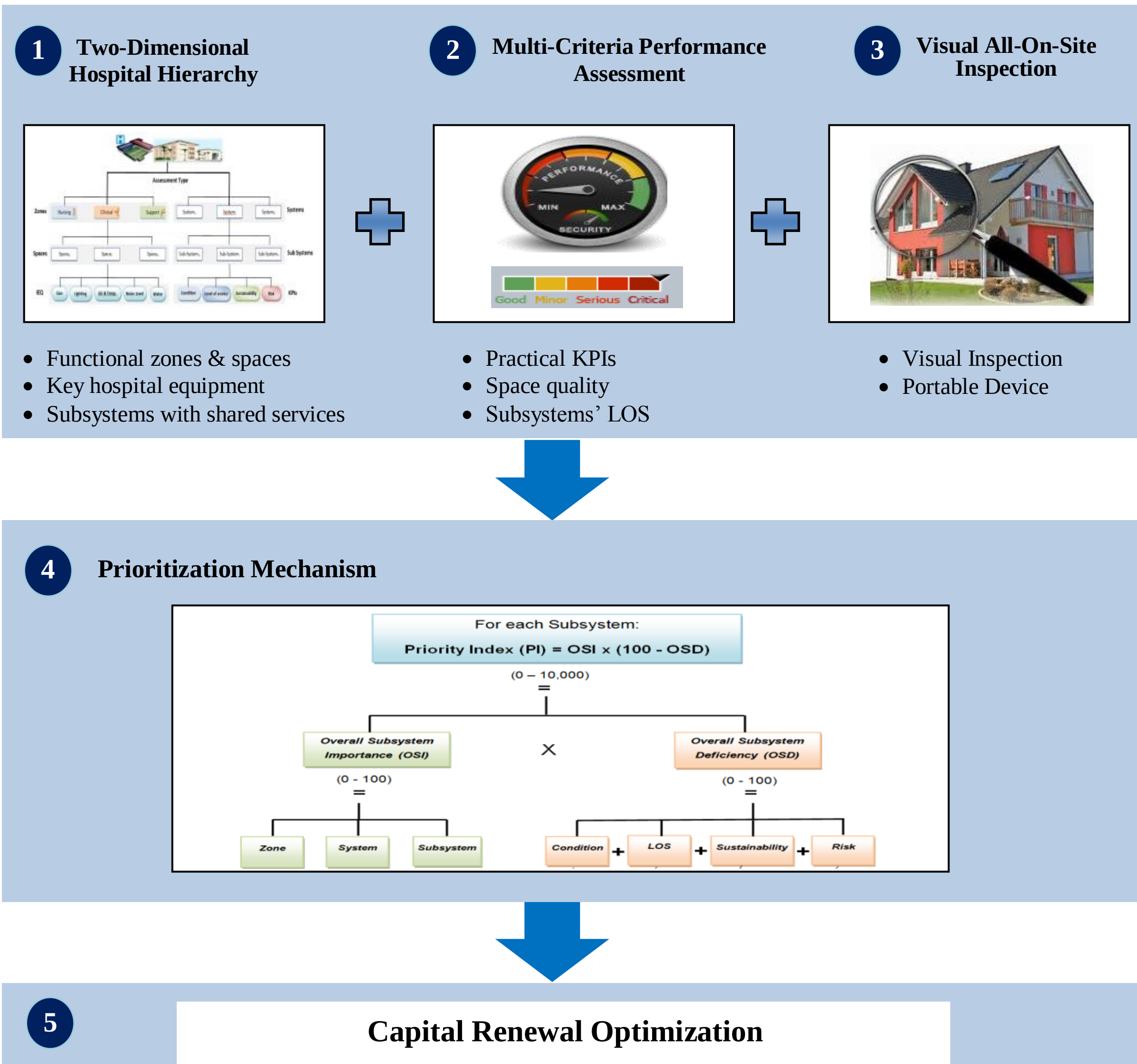


Figure 3.2 Main functions of the proposed framework for performance assessment, prioritization, and capital renewal optimization

The basic hierarchy of hospital systems and subsystems adheres to the UNIFORMAT II classification (UNIFORMAT II, 2005), as shown in the top part of Figure 3.3. In addition to the four main physical systems (civil, architectural, electrical and communications, and mechanical), a fifth "equipment" category (system) has been added. This category relates to specialized (costly) hospital equipment that has been separated from regular mechanical systems because of the importance of keeping these items effectively renewed: MRI machines, CT scanners, and kitchen and laundry equipment. Standardized subsystems in the hierarchy facilitate data integration among the functions (e.g., preventive maintenance, capital renewal, materials/equipment management).

Because of the diversity of space functions in hospitals, a separate hierarchy for hospital spaces has been defined in the new methodology, with three main functional zones, as shown in the lower section of Figure 3.3. Each zone includes a group of spaces that share similar functional characteristics, as follows:

- Clinical zone comprising operating rooms, the intensive care unit (ICU), etc.
- Nursing zone comprised of inpatient rooms, nursing stations, etc.
- Support zone comprising computer room, electrical room, boilers, chillers, etc.

Defining these zones and their relative importance is a unique advantage of the developed system that will lead to better prioritization of assets for renewal. For example, if the clinical zone is assumed to be the most important, then the priority for renewing identical subsystems (or components) must be higher for those in the clinical zone. Similarly, building subsystems that provide shared services to all zones in the hospital, as shown in bold in Figure 3.3, should be assigned higher importance so that they are given higher priority for renewal than subsystems that are localized within a single zone.

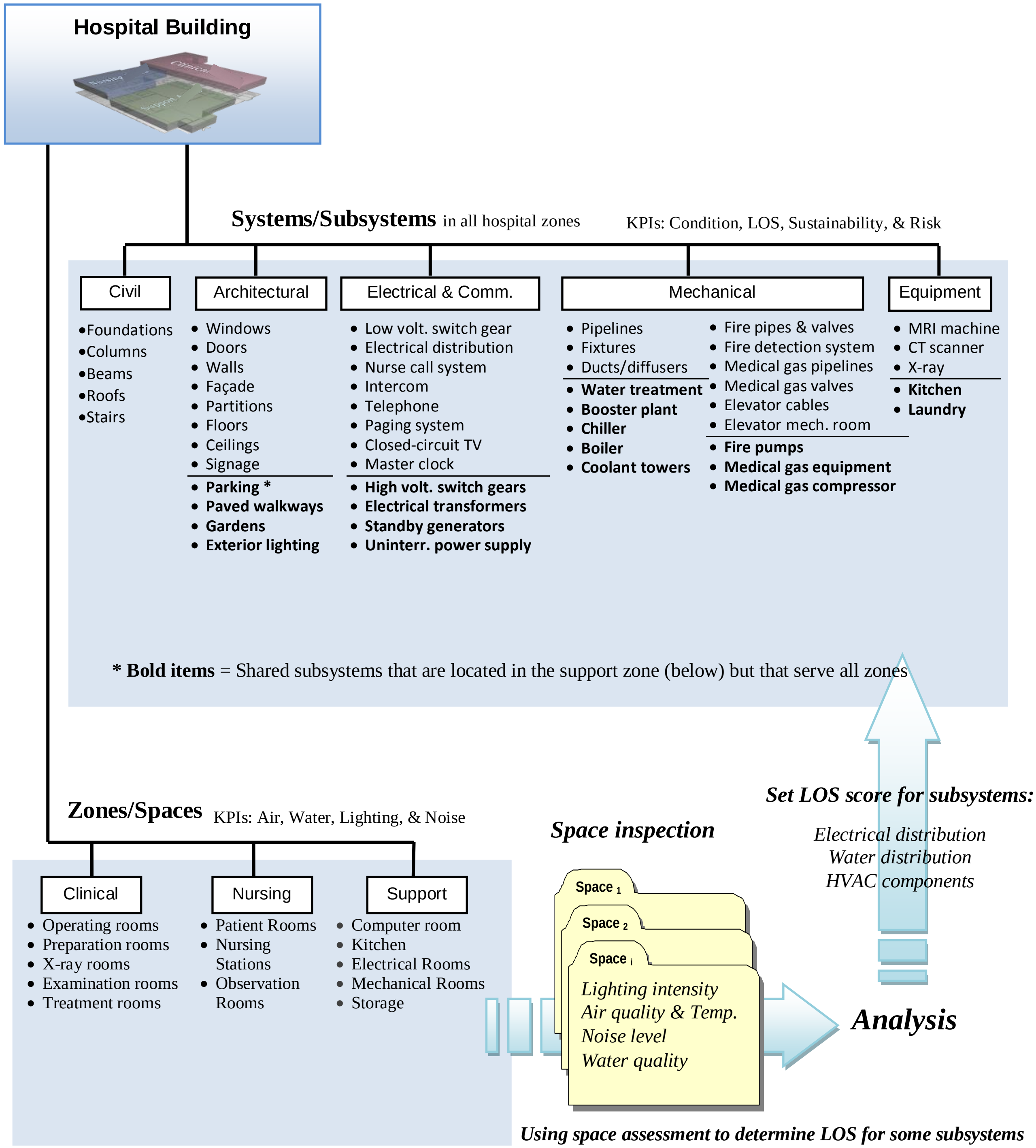


Figure 3.3 Main systems and functional zones

3.3.2 Multi-criteria performance assessment

The combination of the system/subsystem hierarchy and the zone/space hierarchy enables a comprehensive assessment of hospitals. In the developed framework, the system/subsystem hierarchy provides a performance assessment of building subsystems based on four KPIs: condition, LOS, sustainability, and risk. However, for some of the subsystems that affect the quality of spaces (HVAC, water distribution, electrical distribution, etc.), evaluating the LOS is not simple. For these subsystems, the space hierarchy makes it possible to determine a proper LOS value based on an assessment of the spaces in terms of four quality-related KPIs (lighting intensity, air quality and temperature, noise level, and water quality). For example, several spaces showing inadequate water quality/quantity implies a low LOS for the water supply system, as highlighted at the bottom right-hand corner of Figure 3.3.

For the assessment of hospital subsystems, the four KPIs (condition, LOS, sustainability, and risk) vary with respect to both the complexity of the assessment they provide and their applicability to various subsystems, as shown in Figure 3.4, Generally, however, condition assessment is the easiest to perform and can be applied to all subsystems. Sustainability and LOS indicators, on the other hand, are more difficult to determine and apply to a small group of subsystems. Risk of failure is hardest to assess but applies only to major equipment and subsystems within the hospital. As shown in Figure 3.4, the initial expectation was therefore that risk of failure analysis would apply to only about 5 % of hospital subsystems, those involving major electrical and mechanical systems. Figure 3.4 also shows that the condition indicator for all subsystems is assessed visually using a direct rating approach (good, fair, poor, or critical), which provides a sufficient level of detail for renewal purposes (Uzariski 2002). The LOS indicator, on the other hand, assesses the quality of service offered to stakeholders, irrespective of physical condition. For example, old equipment that scores high based on the condition KPI may score poorly with respect to LOS due to its old technology and its inability to meet the demands of the current workload. As mentioned, for some specific subsystems (HVAC, water distribution, and electrical distribution), the LOS assessment is determined after the quality of the indoor environment in various spaces has been assessed. Sustainability also applies to a small subset of the hospital subsystems and is based on a direct rating process. Risk, the last type of indicator, applies to key subsystems whose failure affects health, safety, or the environment. In the absence of historical data related to failure rates and consequences, a direct rating approach was used in this research.

Example: KPIs applicable to "water system" and their weights

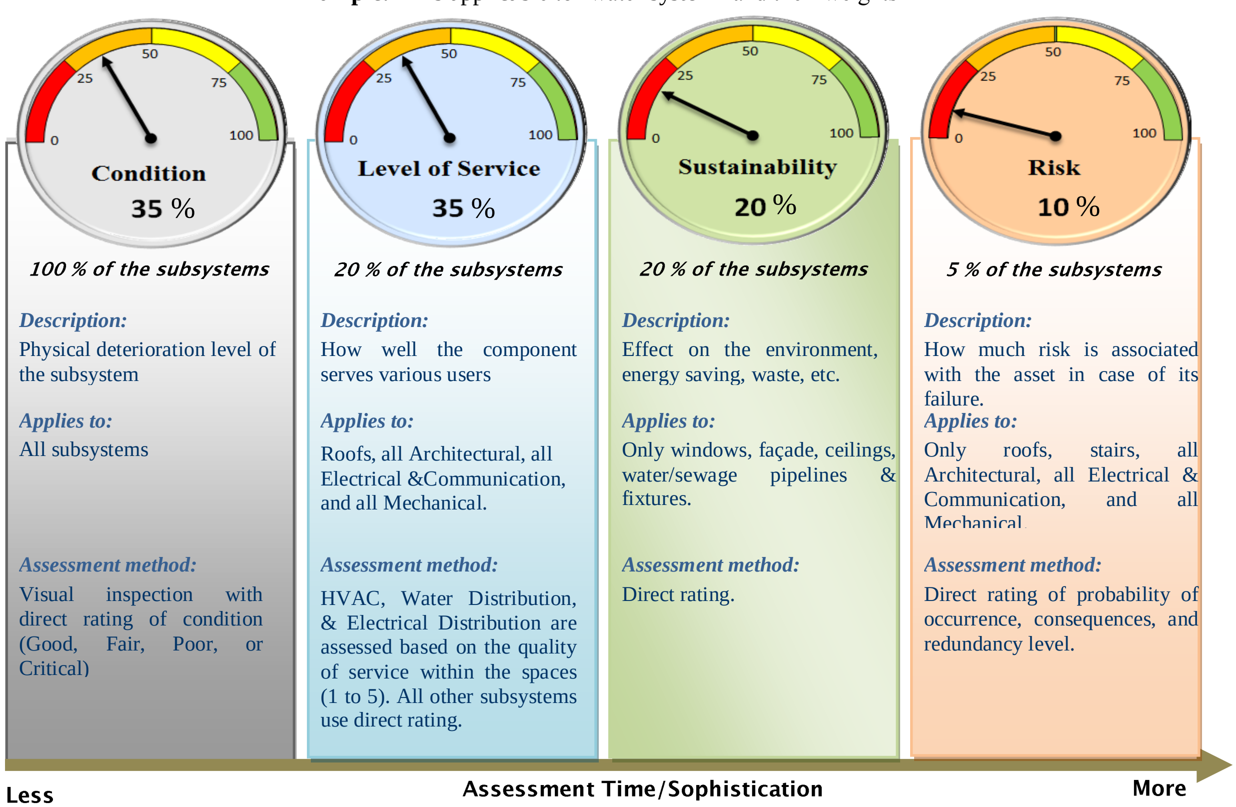


Figure 3.4 Applicability and weights for the various KPIs

For each hospital subsystem, therefore, the first step in the assessment process is to define the applicable KPIs that best measure the performance of that subsystem and their weights, obtained from the results of a survey, as discussed in Chapter 4. For example, foundations are assessed based on condition only, whereas water systems must be assessed in terms of condition (35%), LOS (%35), sustainability (20%), and risk (10%), as shown in Figure 3.4. This process thus focuses the assessment effort and saves the time and cost of producing indiscriminate assessments that are based on all KPIs.

3.3.3 Visual all-on-site inspection

Visual inspection has been considered the most appropriate method for assessing the condition of buildings. Traditional paper-based visual inspection is usually slow, costly, and subjective and requires well-trained assessors. Hegazy et al. (2008) developed a visual inspection application that can be used on an ultra-mobile computer system to make the assessment process cheap, effortless, and non-subjective. Building upon this initial effort, the system developed in the research for this thesis was adapted the application specifically for hospital assessment. Significant effort has been applied to the development and expansion of the capability of the application in order to incorporate the developed two-dimensional hierarchy (i.e., physical systems and the spaces) for hospitals, the four KPIs, and the four IEQ factors, to enhance the comprehensiveness and accuracy of the assessment.

The first step in the design process was to save the hospital building hierarchy into a database with a predefined list of 180 systems (e.g., civil) and subsystems (e.g., foundations), as shown in Figure 3.5. To facilitate the inspection process, each subsystem in the building hierarchy is allocated a fixed set of four instances (good, fair, poor, and critical). These terms are clearly defined in the application, with several photographs included for each category as a means of reducing inspection subjectivity. The interactive inspection application for hospitals can be used on handheld tablets, as shown in Figure 3.6. The application has been designed so that all inspection work, for either subsystem assessment or space assessment, is conducted completely on-site, without the need for additional work at the inspector's office.

Once the assessor selects a subsystem for inspection (e.g., windows, as shown in Figure 3.6), a simple data entry form appears, which allows access to the four instances (good, fair, poor, critical) for that subsystem. The related background floor plan also retrieves and shows the locations of the instances. When one of the condition instances is selected (Critical instance in the sample shown in Figure 3.6), the user is prompted to view the inspection data associated with that instance for that subsystem, as shown in Table 3.1.

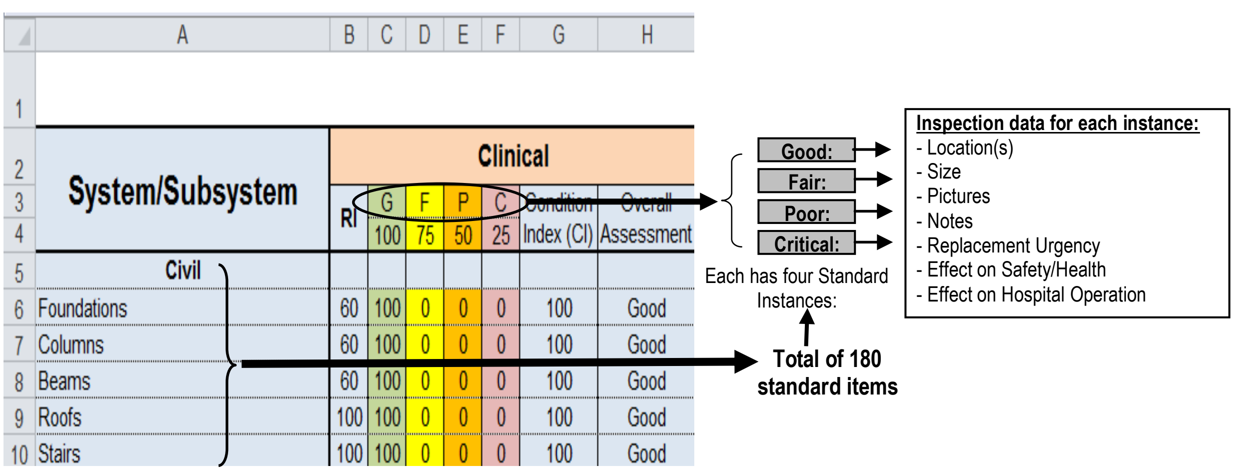


Figure 3.5 Portion of the standardized building hierarchy and inspection data structure (Heghazy et al. 2008)

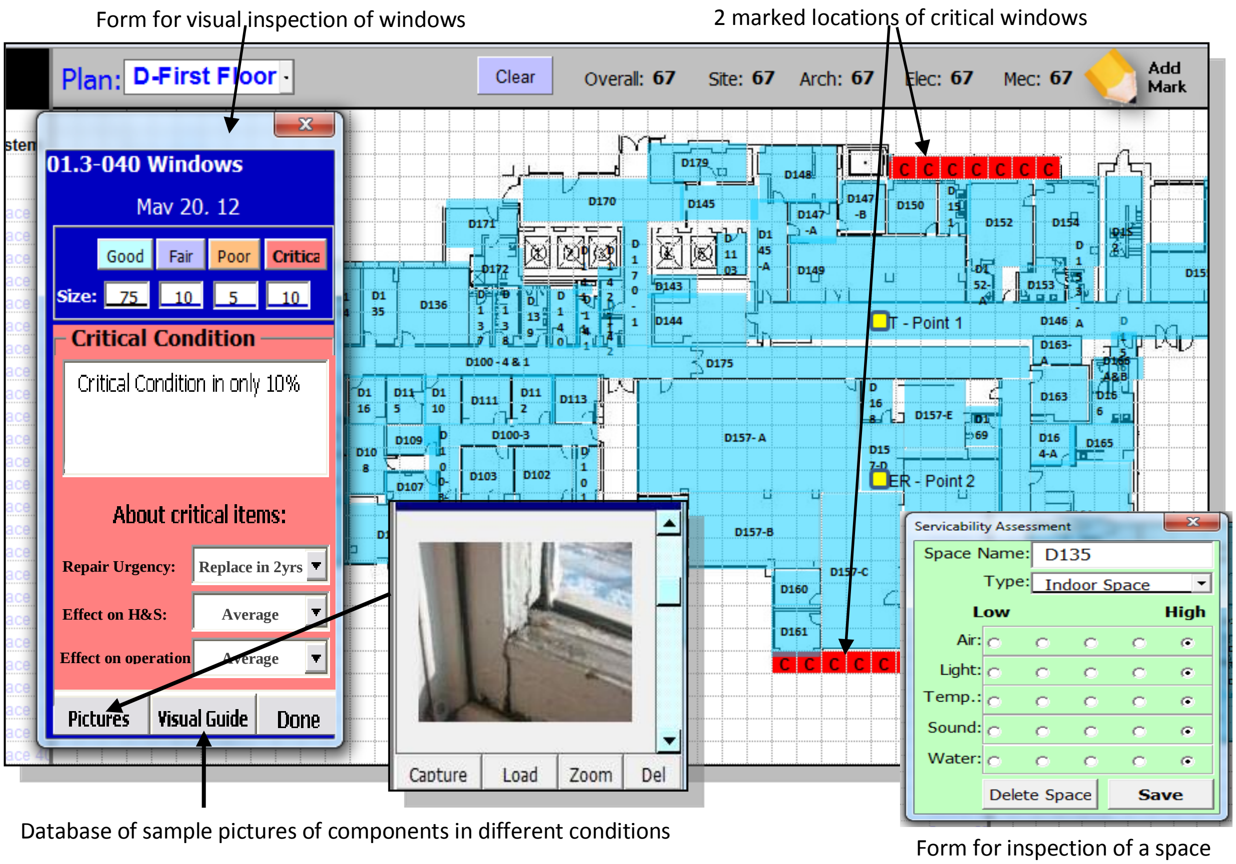


Figure 3.6: Visual inspection system for handheld tablets

Table 3.1: Sample inspection data for an instance (Critical) of a subsystem (Windows)

Data	Description
Location(s):	User selects the cells on the floor plan, which are colour coded to indicate condition.
Size:	Relative sizes (%) of the four condition instances (Good, Fair, Poor, and Critical).
Pictures:	Pictures taken are coded automatically and saved in the inspection database.
Notes:	Additional text comments.
Replacement Urgency:	Options: Replace Immediately, Replace in 1 year, Replace in 2 years, Not Urgent.
Effect on Safety/Health:	Options: Very High, High, Medium, Low, and Very Low.
Effect on Operation:	Options: Very High, High, Medium, Low, and Very Low.

Based on the data "Size" listed in Table 3.1, the overall Condition Index (CI) for each subsystem is calculated as follows:

$$CI = \frac{\sum_{i=1}^{4} (CS_i \cdot Size_i)}{\sum_{i=1}^{4} Size_i} \qquad \textbf{(3.1)}$$

Where CS_i is the scale value of each subsystem (good = 100, fair = 75, poor = 50, and critical = 25), and $Size_i$ is the relative size (percentage or number of items) of each condition subsystem as entered by the user during inspection. The structure of the inspection data for any building therefore includes a fixed set of records associated with the total number of instances that can be inspected. This standardization facilitates the automation and comparison of the hospital's data. It should be noted that the user does not enter all of the data for all instances in a building. The system's default settings are that all subsystems are assigned a value of 100% for their "Good" instances. As subsystems deteriorate, the inspectors can then add information to the "Poor" or "Critical" instances only. The CI for the subsystem is then automatically calculated accordingly based on the percentage of the scale value of each subsystem and the size of each condition subsystem, as shown in Figure 3.7.

Foundation (CI) = (100x100 + 0x75 +0x50 + 0x25) / (100+0+0+0) = 100 **(Equation 3.1)**

	A	B	C	D	E	F	G	H
1								
2	Subsystem	Clinical						
3		RI	G	F	P	C	Condition Index (CI)	Overall Assessment
4			100	75	50	25		
5	Civil							
6	Foundations	30	100	0	0	0	100	Good
7	Columns	30	100	0	0	0	100	Good
8	Beams	30	100	0	0	0	100	Good
9	Roofs	100	100	0	0	0	100	Good
10	Stairs	100	100	0	0	0	100	Good
11	Architectural							
12	Windows	100	0	0	100	0	50	Poor
13	Doors	100	0	0	100	0	50	Poor
14	Walls	30	0	100	0	0	75	Fair

	A	I	J	K	L	M	N	O
2	Subsystem	Nursing						
3		RI	G	F	P	C	Condition Index (CI)	Overall Assessment
4			100	75	50	25		
5	Civil							
6	Foundations	30	100	0	0	0	100	Good
7	Columns	30	100	0	0	0	100	Good
8	Beams	30	100	0	0	0	100	Good
9	Roofs	100	100	0	0	0	100	Good
10	Stairs	100	100	0	0	0	100	Good
11	Architectural							
12	Windows	100	0	0	100	0	50	Poor
13	Doors	100	0	0	100	0	50	Poor
14	Walls	30	0	100	0	0	75	Fair

	A	P	Q	R	S	T	U	V
2	Subsystem	Support						
3		RI	G	F	P	C	Condition Index (CI)	Overall Assessment
4			100	75	50	25		
5	Civil							
6	Foundations	30	100	0	0	0	100	Good
7	Columns	30	100	0	0	0	100	Good
8	Beams	30	100	0	0	0	100	Good
9	Roofs	100	100	0	0	0	100	Good
10	Stairs	100	100	0	0	0	100	Good
11	Architectural							
12	Windows	100	0	100	0	0	75	Fair
13	Doors	100	0	100	0	0	75	Fair
14	Walls	30	0	100	0	0	75	Fair

Figure 3.7: Physical condition: Condition Index

The second step and a key productivity feature is that the inspection application includes the hospital hierarchy and all of the 2D floor plans of the hospital (with all spaces predefined). The inspector is then able to use a stylus pen to mark the location of problem areas directly on the drawings. For example, Figure 3.6 shows the location of critical windows marked on the first-floor plan, in the section covering parts of the north and south sides of the building. This feature provides a visual location reference for the inspection data. As further assistance in the assessment of the condition of the subsystem, the application allows the inspector to take photos using the built-in digital camera, to annotate the photos with handwritten notes, and to compare the photo taken with the visual guide photos, as shown in Figure 3.6. The photos are automatically associated with the subsystem under inspection and are stored appropriately. The inspection application also offers the capability of selecting any space on a 2D floor plan and assessing the quality of its indoor factors (lighting, air, noise, and water) on a scale from 1 (low) to 5 (high), as shown in the inspection form at the bottom right-hand corner of Figure 3.6. The LOS score for the affected hospital subsystems is then automatically calculated based on the percentage of spaces that have indoor quality issues, as shown in Figure 3.8. In addition, during the inspection of any space, IEQ deficiency within each space (i.e., local defects) can be identified and documented, as shown in Figure 3.8, with the accumulation of the defects reflecting the overall deficiency in the related subsystem:

$$IEQdeficiency = 100 - \left(\sum_{i=1}^{n} IEQ_i . RI_i\right) / \left(\sum_{i=1}^{n} RI_i\right) \quad \textbf{(3.2)}$$

Where IEQ deficiency is the local deficiency, IEQ_i is the IEQ assessment score for the indoor environment quality factor, and RI_i is the relative importance of the IEQ factor. An illustrative sample is shown in Figure 3.8.

$$\text{ICU (Local Deficiency)} = [100 - (100\times21+100\times29+100\times21+80\times29) / (21+29+21+29)] = 5.8 \qquad \textbf{(Equation 3.2)}$$

Ground Floor - Indoor Environment Quality (IEQ) Assessment

Type	No.	Area (m2)	RI	Zone	IEQ factors				IEQ	IEQ deficiency
					Lighting	Air	Noise	Water		
					21%	29%	21%	29%		
Intensive Care Unit (ICU)	G1	125	10	20	100	100	100	80	94.2	5.8
Bath 1	G1	5.5	6	60	100	100	100	80	94.2	5.8
Bath 2	G1	5.5	6	60	100	100	100	80	94.2	5.8
Bath 3	G1	5.5	6	60	100	100	100	80	94.2	5.8
Bath 4	G1	5.5	6	60	100	100	100	80	94.2	5.8
Bath 5	G1	5.5	6	60	100	100	100	80	94.2	5.8
Corridor 1	G1	31	2	60	100	100	100	N/A	100	0
Corridor 2	G1	72	2	60	100	100	100	N/A	100	0

Figure 3.8: Sample assessment of indoor environment quality and level of service

In summary, the developed visual inspection system incorporates the following features:

- The use of a two-dimensional hospital hierarchy best service the hospital environment
- The user-friendly interface provides the ability to mark the location of the subsystem under assessment directly on 2D digital floor plans using four-colour coding to represent Good, Fair, Poor, or Critical items.
- The system is easy to install and use on any handheld tablet, which expedites the inspection.
- Photographs of the assessed subsystem can be saved directly in a location-based database.
- A built-in pictorial database of components in different conditions provides visual guidance during inspection, which reduces subjectivity.
- The visual guide offers the user the opportunity to visually compare the pictures provided with the real condition of the subsystem under assessment, thus enabling a quick, simple, and accurate assessment.

Based on expert input and the physical condition assessment of the hospital building systems, the overall subsystem importance (OSI), the overall subsystem deficiency (OSD) (i.e. Performance), the overall subsystem priority index (OSPI), and the overall building performance index (OBPI) can be identified. The formulations for determining these indices are discussed in the next section.

3.4 Calculation of Performance Indices

3.4.1 Overall subsystem importance

The OSI level reflects the importance of each system according to its location in the hospital building. The determination of the OSI is the first essential step in the calculation of the overall priority index for each subsystem (OSPI). The overall importance of each subsystem (OSI) is calculated from the multiplication of the relative importance of the subsystem, the relative importance of the system to which this subsystem belongs, and the relative importance of its zone, as shown in the lower left-hand portion of Figure 3.9. When a subsystem is in a more important zone or system, its OSI is therefore higher, and the (OSPI) becomes correspondingly higher, indicating greater eligibility for renewal. For example, the water treatment (shared subsystem) in the support zone has a higher OSI than the walls (non-shared subsystem) in the nursing zone; therefore, shared subsystems are assigned 25 % more importance than non-shared subsystems because they provide services for all of the zones and spaces in the building.

3.4.2 Overall subsystem deficiency

The OSD is the second essential component in the calculation of the priority index for each subsystem (OSPI), and it represents the weighted sum of the deficiencies for all applicable KPIs associated with the subsystem. Calculating the OSD requires special care in order to avoid misrepresentation. Once the subsystem has been assessed in the field and the scores for its condition, LOS, sustainability (all from 0 to 100) have been determined, the subsystem's OSD value is then established as the weighted sum of these scores, as shown in the lower right-hand portion of Figure 3.9. An examination of the equations in Figure 3.9, however, reveals the careful use of the score values. For example, for the first three indicators (condition, LOS, and sustainability), the value used in the equation is (100- condition index score) based on consideration of a linear relationship between these KPIs. Thus, when the subsystem's condition score, for example, is high, using (100- condition index score) in the equation results in a small OSD value, and accordingly, a low OSPI for the renewal of this subsystem. Risk, however, is dealt with in a different manner. To facilitate risk calculations, the value of the risk associated with the subsystem is determined based on its probability of failure (assumed to be 100- condition index score) multiplied by the consequence score (High = 100, Medium = 70, and Low = 40) and then by an adjustment value (Partial = 50 %; Full = 10 %; and Double = 2 %) that represents the existing redundancy level of the subsystem. This formulation means that the impact of the condition, consequence, and redundancy have an appropriate effect on the OSPI calculation. A OSPI of zero for a subsystem indicates that its performance is high: the subsystem has a low renewal priority. On the other hand, when a subsystem has a high deficiency value that renders the overall condition of the subsystem less than the minimum acceptable condition level, then that subsystem will be eligible for renewal work.

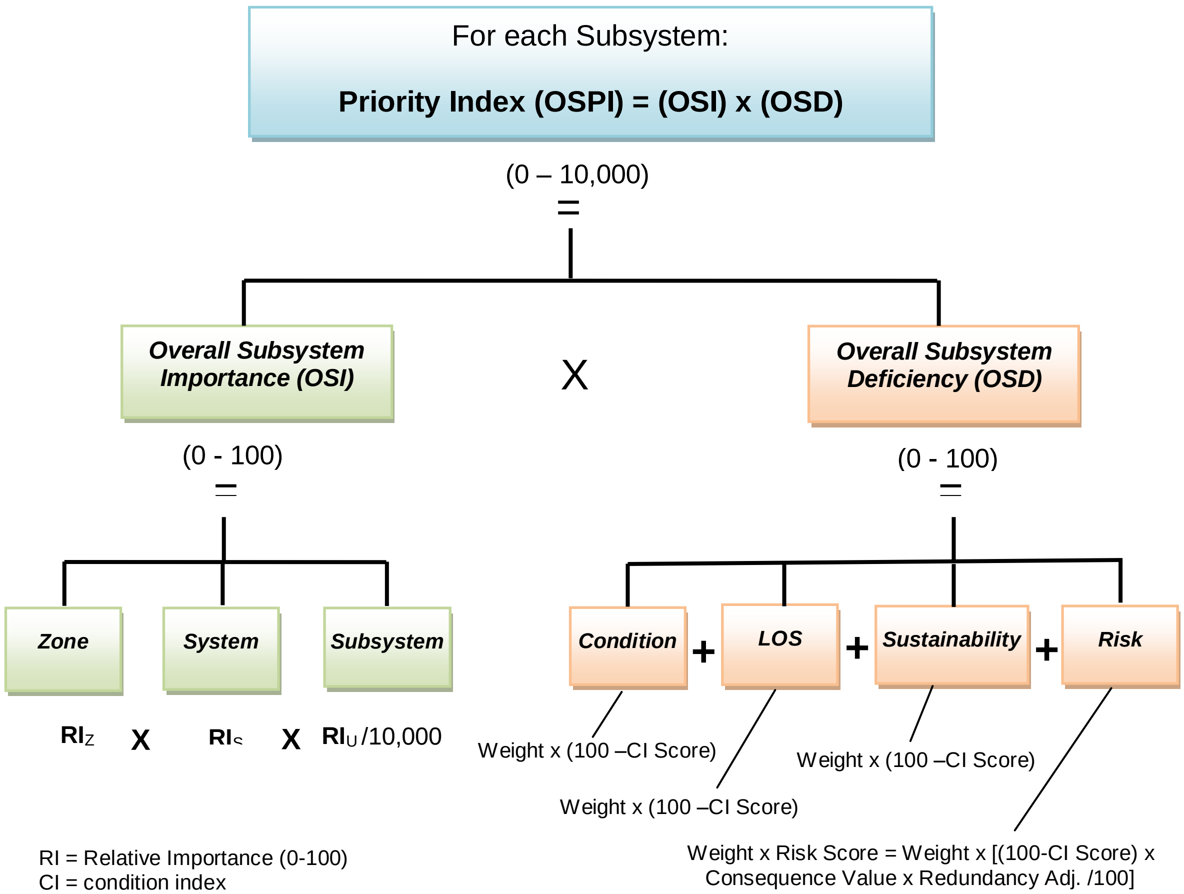
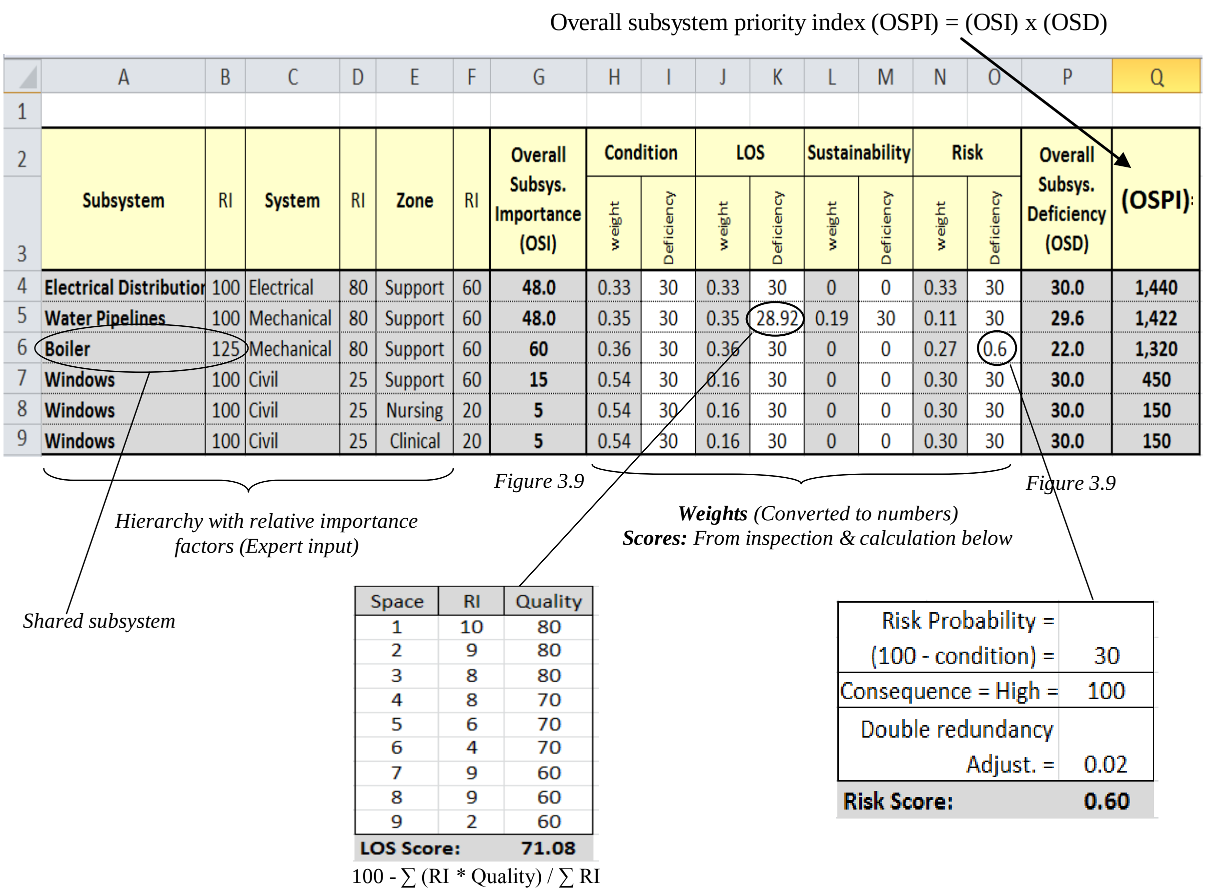


Figure 3.9: Calculation of the priority index for a subsystem

3.4.3 Overall subsystem priority index

To demonstrate the developed prioritization analysis, a hypothetical example involving six different subsystems (electrical distribution, water pipelines, boiler, and three roof sections) was considered. The priority analysis calculation is shown in Figure 3.10, with each of the analyzed subsystems in a separate row. Of these subsystems, the boiler is considered to be a shared subsystem; i.e., it is part of the support zone but serves all zones, as highlighted in Figure 3.3. The three roof sections also relate to three hospital zones: clinical, nursing, and support. These six subsystems have been selected because they provide a demonstration of a scenario that includes a variety of competing subsystems from different zones and systems and that also involves both shared and non-shared subsystems, subsystems that have an impact on the indoor quality of spaces, and subsystems that are sensitive to the risk of failure.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1																	
2	Subsystem	RI	System	RI	Zone	RI	Overall Subsys. Importance (OSI)	Condition		LOS		Sustainability		Risk		Overall Subsys. Deficiency (OSD)	(OSPI)
3								weight	Deficiency	weight	Deficiency	weight	Deficiency	weight	Deficiency		
4	Electrical Distributior	100	Electrical	80	Support	60	48.0	0.33	30	0.33	30	0	0	0.33	30	30.0	1,440
5	Water Pipelines	100	Mechanical	80	Support	60	48.0	0.35	30	0.35	28.92	0.19	30	0.11	30	29.6	1,422
6	Boiler	125	Mechanical	80	Support	60	60	0.36	30	0.36	30	0	0	0.27	0.6	22.0	1,320
7	Windows	100	Civil	25	Support	60	15	0.54	30	0.16	30	0	0	0.30	30	30.0	450
8	Windows	100	Civil	25	Nursing	20	5	0.54	30	0.16	30	0	0	0.30	30	30.0	150
9	Windows	100	Civil	25	Clinical	20	5	0.54	30	0.16	30	0	0	0.30	30	30.0	150

Space	RI	Quality
1	10	80
2	9	80
3	8	80
4	8	70
5	6	70
6	4	70
7	9	60
8	9	60
9	2	60
LOS Score:		**71.08**

Risk Probability = (100 - condition) =	30
Consequence = High =	100
Double redundancy Adjust. =	0.02
Risk Score:	**0.60**

Figure 3.10: Subsystem priority index calculations

The left-hand side of the figure shows the hierarchy of the subsystems, systems, and zones, with their relative importance (RI) factors that have been determined based on the survey tables (zone and system RIs from Table 4.3; and subsystem RIs from Table 4.6, Table 4.7, Table 4.8, and Table 4.9).

Column G shows the OSI calculated for each subsystem, following the formulation shown in Figure 3.9. The middle section of Figure 3.10 also shows the assessment scores for the KPIs related to each subsystem (based on the inspection). The KPI weights are obtained from Table 4.6, Table 4.7, Table 4.8, Table 4.9, and Table 4.10. All of the scores for the condition and sustainability KPIs are determined based on the inspector's direct rating. The LOS and risk scores, however, require detailed calculations. As an example, the circled 28.92 (100-71.08) score for the LOS for the water pipelines is calculated based on the assessment of the spaces, as shown at the bottom of Figure 3.10, and the circled 0.6 score for the risk assessment for the boiler is established as shown in the bottom right-hand corner of Figure 3.10. Based on all of these scores and following the calculation scheme illustrated in Figure 3.9, the overall priority index (OSPI) for each of the six subsystems is calculated and indicated in the last column of Figure 3.10, where the scores are sorted in descending order: the top subsystem (electrical distribution) listed is the one most eligible for renewal action.

An examination of the OSPI values listed in Figure 3.10 reveals that the proposed prioritization framework demonstrates logical computation and the ability to differentiate among competing assets. The following observations can be made with respect to Figure 3.10 and the overall framework:

- Of all the subsystems, the three windows subsystems (rows 7, 8, and 9) exhibit the worst deficiency (OSD = 30, column P in the Figure 3.10 spreadsheet). However, their smaller OSI scores put them at the bottom of the list, with the windows of the support zone (row 7) having a higher rating than the other two (rows 8 and 9).
- The boiler (row 6) is a shared subsystem, and as such, its RI is raised by 25 %. Although the OSI value is very high and the condition deficiency is identical to those of the other subsystems, its very low risk deficiency places it in third priority.

- Within the support zone, subsystems no. 1 (row 4) and 2 (row 5) both have the same OSI (48, column G) as well as equal condition and risk scores. However, since subsystem 1 has a higher LOS deficiency score, it is assigned a higher priority than subsystem No. 2.

The final results produced by the developed approach provide a reasonably wide range of OSPI values (column Q), which is beneficial because the assignment of the same priority level to too many subsystems can create a problem when fund allocation decisions are being made.

3.4.4 Overall building performance index

The OBPI reflects the overall performance of the entire hospital building. The OBPI is calculated by aggregating the subsystem performance values (e.g., Figure 3.11) to the upper levels (system, zone, and building levels), following equations 3.3 to 3.6, as schematically shown in Figure 3.11. With the performance values of any subsystem_i being ($\text{Subsys.}_i = 100 - \text{OSD}_i$), then, the performance score at the system level becomes (Sys._i, Equation 3.4) is the weighted summation of the subsystems' performance scores, weighted by the relative importance (RI_i) of the involved subsystems. Afterwards, the performance scores at the zone level (Zone_i) and the building level (OBPI) are similarly calculated. The detailed equations are as follows:

Performance at the subsystem level:

$$Subsys._i = 100 - OSD_i \qquad \textbf{(3.3)}$$

Performance at the system level:

$$Sys._i = \sum_{i=1}^{n} Subsys_i . RI_i \Big/ \sum_{i=1}^{n} RI_i \qquad \textbf{(3.4)}$$

Performance at the zone level:

$$Zone_i = \sum_{i=1}^{n} Sys_{.i}.RI_i / \sum_{i=1}^{n} RI_i \qquad \textbf{(3.5)}$$

Performance at the building level:

$$OBPI = \sum_{i=1}^{3} Zone_i.RI_i / \sum_{i=1}^{3} RI_i \qquad \textbf{(3.6)}$$

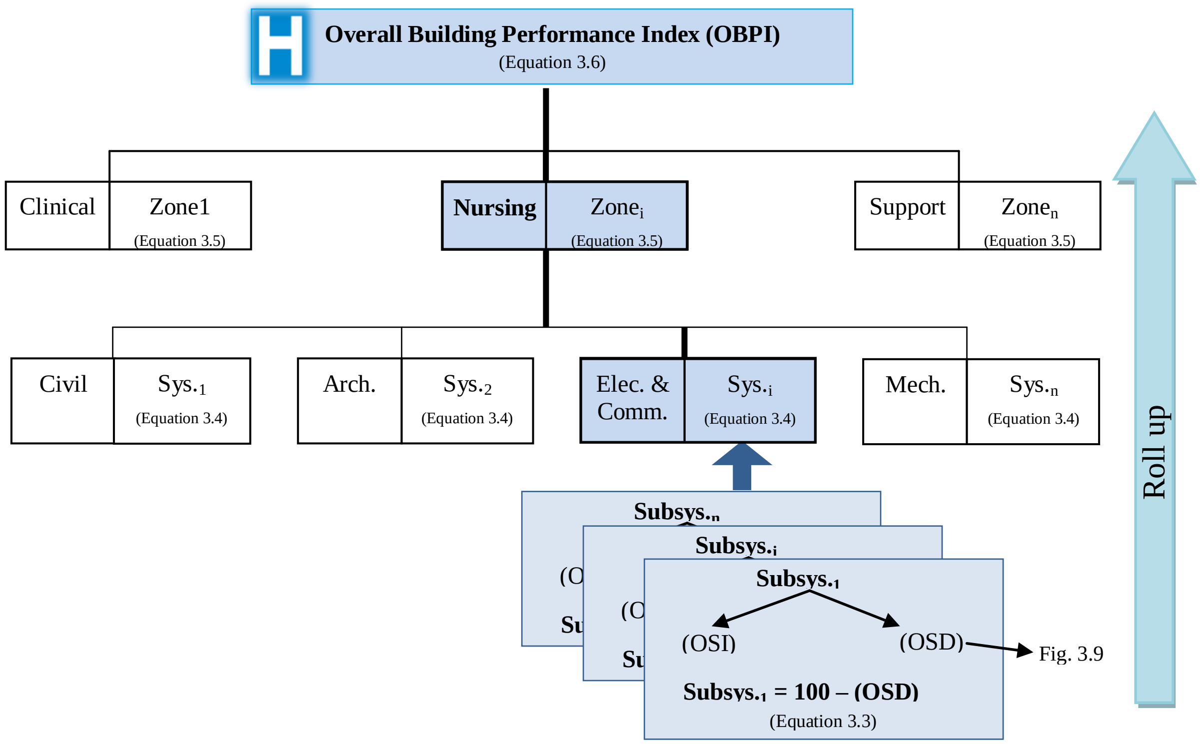


Figure 3.11: Calculation of the OBPI

Figure 3.12 shows the overall building performance index (OBPI) for the case study 1 (hospital 1), that is discussed later in chapter 5, where the performance at all the hospital hierarchy levels were calculated using the equations 3.3, 3.4, 3.5, and 3.6.

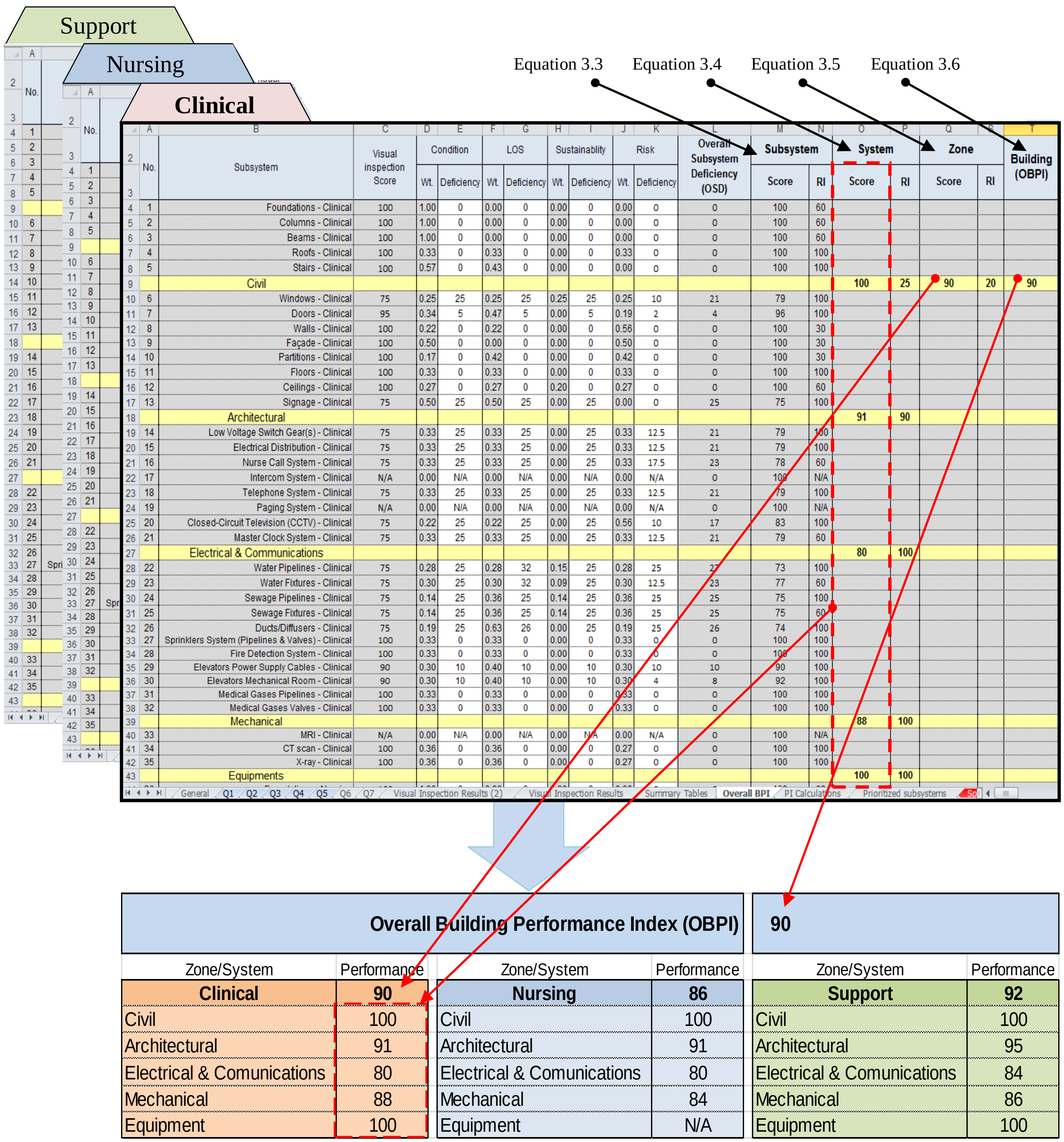


Figure 3.12: Example of performance indices at hospital hierarchy's levels

3.5 Conclusions

This chapter has introduced the first four functions of the proposed framework for performance assessment, prioritization, and capital renewal optimization; a two-dimensional hierarchy of hospital systems/spaces, a multi-criteria performance assessment process, a visual all-on-site inspection process, and a prioritization mechanism. All of these functions are used in order to identify the overall subsystem importance (OSI) and the overall subsystem deficiency (OSD), based on which the overall priority index (OSPI) can be determined for each subsystem in order to provide assistance with the setting of renewal plans. The overall building performance index (OBPI) calculation was also introduced. The fifth function of the proposed framework, capital renewal optimization, is discussed in Chapter 6.

The next chapter explains the data collection methodology that was followed for collecting the required data from the four hospitals surveyed and provides an analysis of these data, which were used for the validation of the prioritization portion of the developed framework.

Chapter 4

Data Collection and Framework Development

4.1 Introduction

This chapter introduces the methodology used for the collection of data from four hospitals, which formed the basis for the development and validation of the proposed framework. The survey questionnaire and an analysis of the data collected are then presented, along with comments about the proposed framework.

4.2 Data Collection Survey

For the drafting of an integrated assessment methodology for hospital buildings, significant effort was directed at soliciting feedback from the maintenance professionals (not the patients and the medical staff) about its practicality and also to obtain case study data to be used for the development and validation of the system. To acquire this expert input, a survey questionnaire was developed, and a user-friendly Excel spreadsheet was chosen as a means of facilitating interactive interview sessions. Because hospital maintenance professionals are often too busy to complete lengthy paper-based surveys, the questionnaire was carefully designed to reduce data entry time, to maintain the interest of the interviewees, and to obtain the most complete and accurate data possible. Spreadsheet functions and macros were used in the survey spreadsheets so that the interviewee could easily select a variety of options from dropdown menus and thus quickly complete the survey. Before the hospital professionals were approached, a draft survey was first tested for comprehensibility and then iteratively modified, as shown in steps 1 to 3 of Figure 4.1. The Delphi approach (Hallowell and Gambatese 2010) was selected for the research methodology because it provides a method of acquiring accurate data based on the systematic, interactive, and iterative collection of expert opinions during interview sessions.

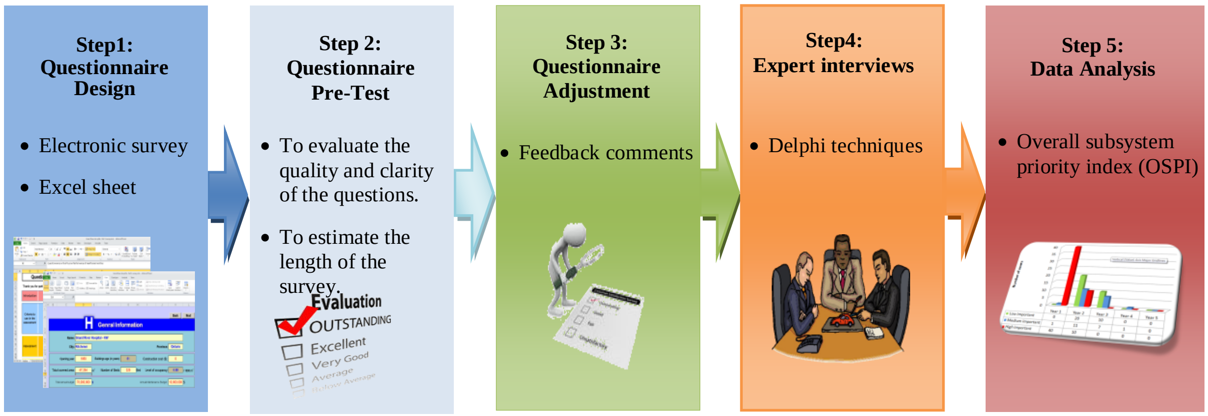


Figure 4.1: Steps of the data collection

The survey questionnaire is divided into two parts. Part 1, as shown in Figure 4.2, includes two sections related to general information about the hospital, and seven questions that define the criteria to use in the assessment of relative importance factors, hospitals: KPIs at different levels, etc. Part II of the survey is focused on the collection of data related to the existing maintenance history, maintenance policy, and available decision support tools (Ali and Hegazy 2013a). Both parts are discussed in the following subsections.

Introduction		General information about the Hospital
Criteria to use in the assessment	Q1:	Relative importance of the zone types
	Q2:	Relative importance of the different disciplines in a zone type
	Q3:	Minimum acceptable condition for each discipline
	Q4:	Importance of each subsystem to its Main System & Repair Options
	Q5:	Practical Key Performance Indicators (KPIs) for the systems in the Clinical, Nursing, and Support zones
	Q6:	Relative importance of the Indoor Environment Quality (IEQ) Factors
	Q7:	Evaluation of the current risk for each building system

Figure 4.2: Part I of the questionnaire survey

4.2.1 Part I of the survey:

Figure 4.3 shows a screenshot of the spreadsheet that was used in order to obtain general information about the hospital: name, location, opening year, age, total covered area, number of beds, level of occupancy, total annual budget, and annual building maintenance budget. The information shown in Figure 4.3 relates to the first hospital case study, as discussed later.

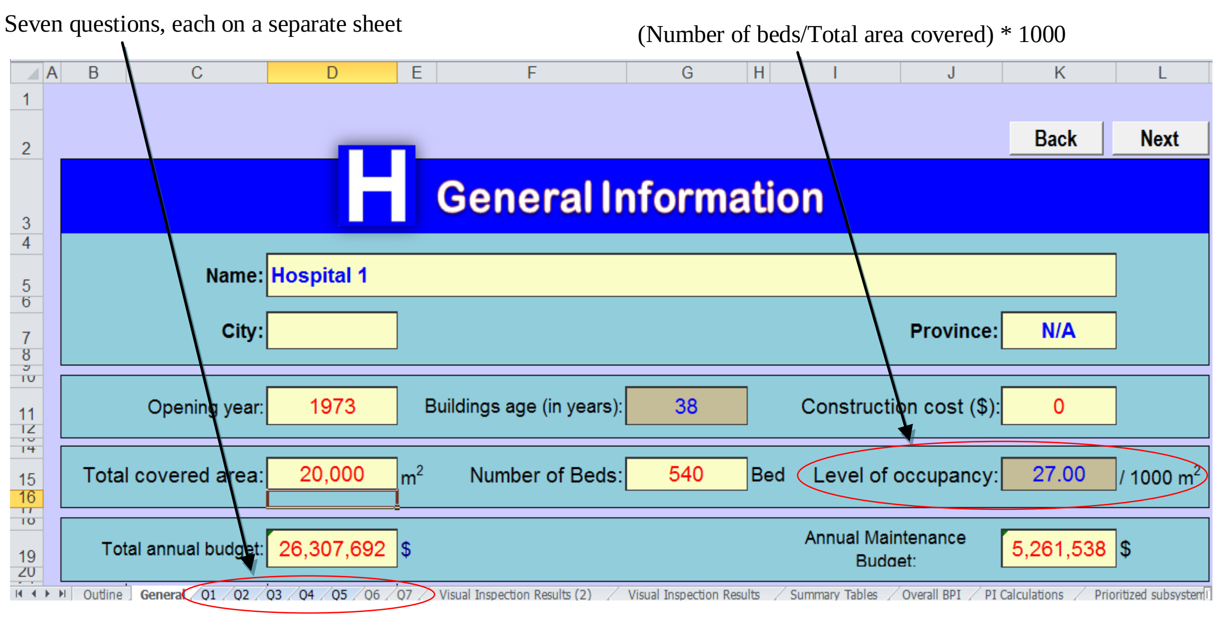


Figure 4.3: General information about the hospital

After the general hospital information is entered, the survey presents seven questions, each on a separate spreadsheet. Figure 4.4 shows the “Q1 spreadsheet” that asks about the relative importance (RI) of each functional zone within the hospital building. In this section, the experts can choose the appropriate choice from the dropdown menu. The (RI) values for each zone are then used as a means of calculating the overall subsystem importance (OSI) value, as discussed earlier and illustrated in Figure 3.9.

As indicated in Figure 4.4, for this hospital, the experts defined the clinical zone as equally important as the nursing zone but as less important than the support zone. The nursing zone is also considered to be less important than the support zone. Once these relative choices are entered, the relative importance value (i.e., weight) is automatically calculated using the Analysis Hierarchy Process (AHP) formulated in a background spreadsheet, as shown in Figure 4.5.

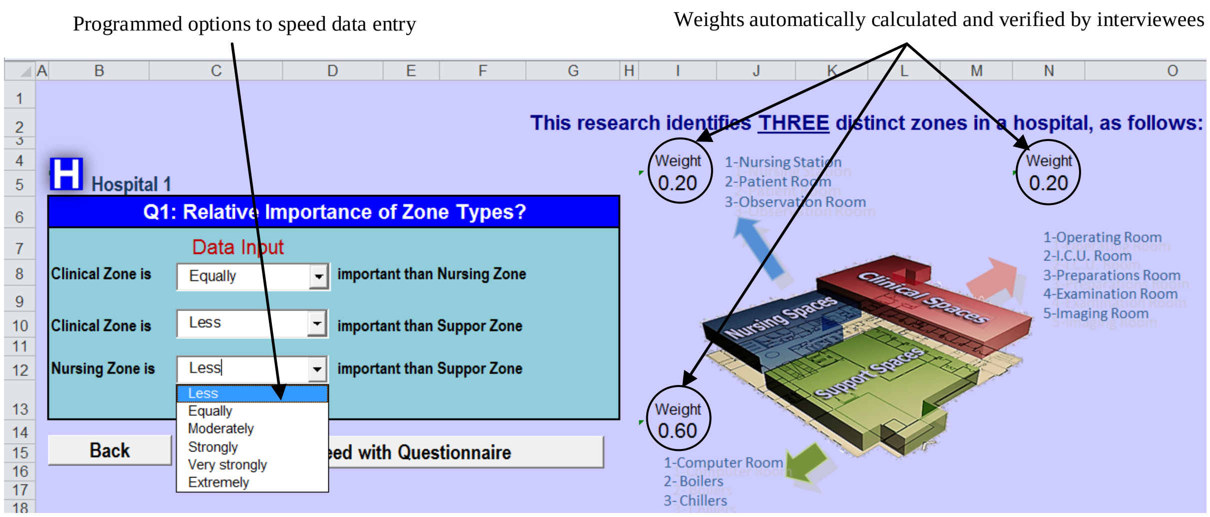
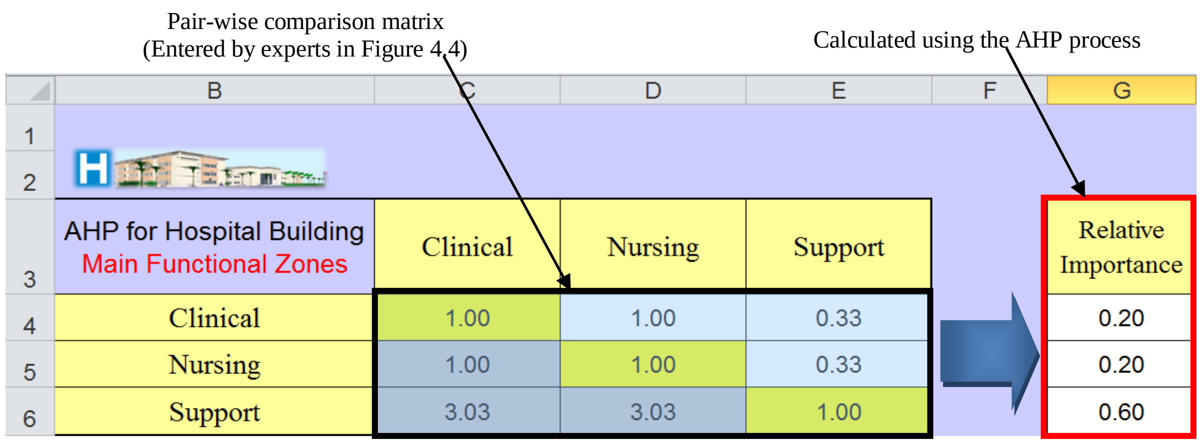


Figure 4.4: Relative importance of each functional zone



AHP for Hospital Building Main Functional Zones	Clinical	Nursing	Support	Relative Importance
Clinical	1.00	1.00	0.33	0.20
Nursing	1.00	1.00	0.33	0.20
Support	3.03	3.03	1.00	0.60

Figure 4.5: AHP spreadsheet for identifying the relative importance of zones

Figure 4.6 shows the “Q2 spreadsheet” that solicits the expert’s opinion with respect to the relative importance (RI) of the main systems within each functional zone, using a scale from 0 (N/A) to 100 (very important). It is interesting to note that no major equipment is located in the nursing zone, for which experts assign an RI of zero. As well, because the support zone includes costly equipment, architectural systems are given a low weight, but the same is not true for the clinical zone.

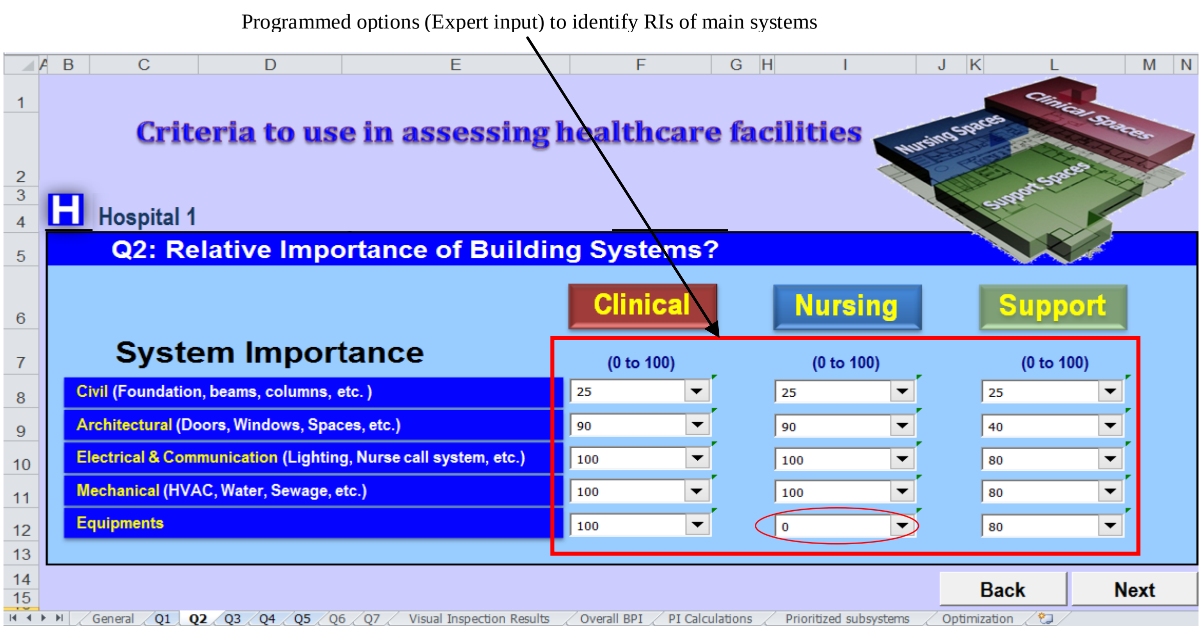


Figure 4.6: Relative importance of each system within each functional zone

Figure 4.7 shows the “Q3 spreadsheet” for soliciting experts’ opinions about the minimum acceptable condition for each system within each functional zone. The minimum acceptable condition is used for determining whether the subsystem is eligible for renewal work based on a comparison of the calculated performance of the related subsystem against this condition. For example, if the overall performance of any subsystem with respect to civil work is 60, and the minimum acceptable condition is 70, as shown in Figure 4.7, (i.e., 60 < 70) then the performance of this subsystem is less than the minimum acceptable condition, and it therefore becomes eligible for renewal.

Condition 60 < 70 (i.e., eligible for renewal)

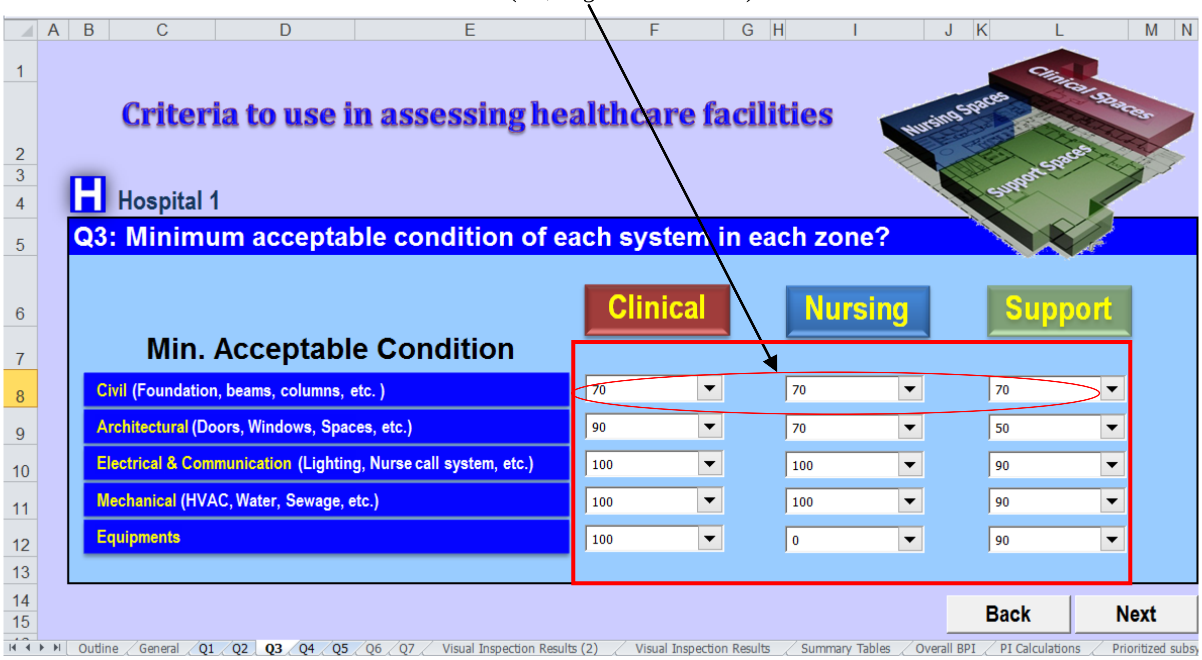


Figure 4.7: Minimum acceptable condition for each system

Figure 4.8 shows the "Q4 spreadsheet" that indicates the importance of each subsystem relative to its parent system. For example, based on the experts' input, roofs have greater importance than foundations in the civil subsystems. The RI of each subsystem is used for identifying the overall subsystem importance (OSI), as discussed in Chapter 3. Figure 4.8 also shows the renewal options and their percentage of the replacement cost.

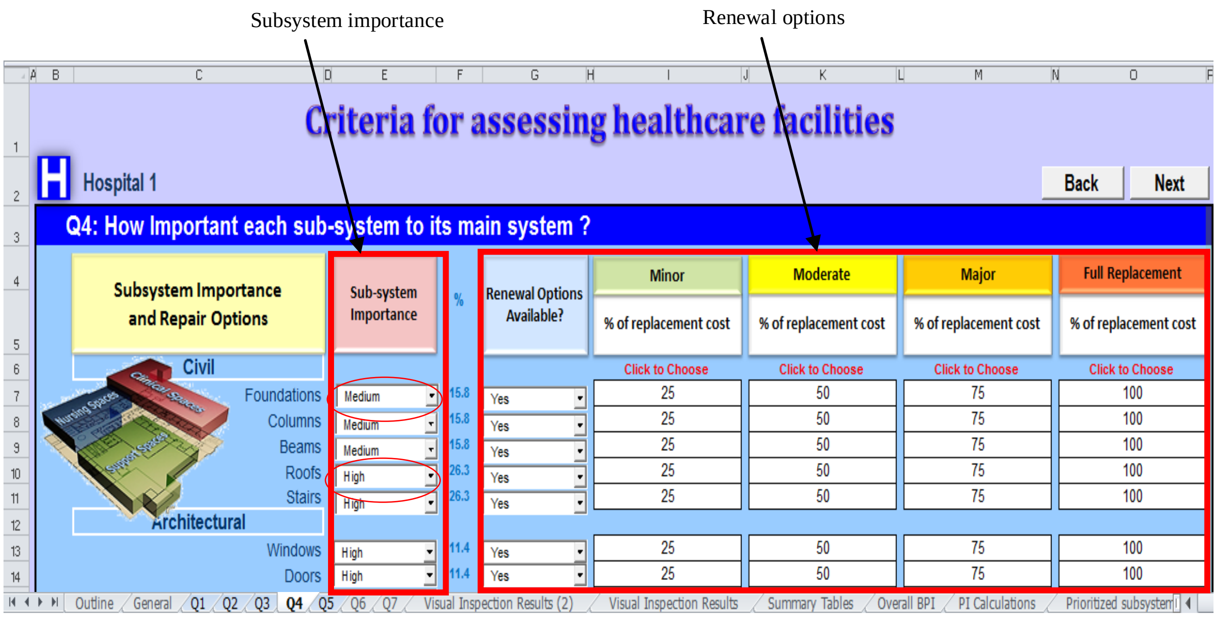


Figure 4.8: Relative importance of each subsystem in its main system and associated renewal options

Figure 4.9 shows the "Q5 spreadsheet," which identifies the applicability of the four KPIs to each subsystem. Based on the interviewees' selection of the descriptive level of importance, the weights of the KPIs are automatically calculated as shown in the figure. For example, the performance of the foundation subsystem is assessed based on condition only, while the performance of windows is assessed with respect to all four KPIs, with equal weight for each: condition, LOS, sustainability, and risk. This process of defining the applicability of the four KPIs to the various subsystems makes the performance assessment process more structured and also automates the computation of the overall performance level based on the field assessment data.

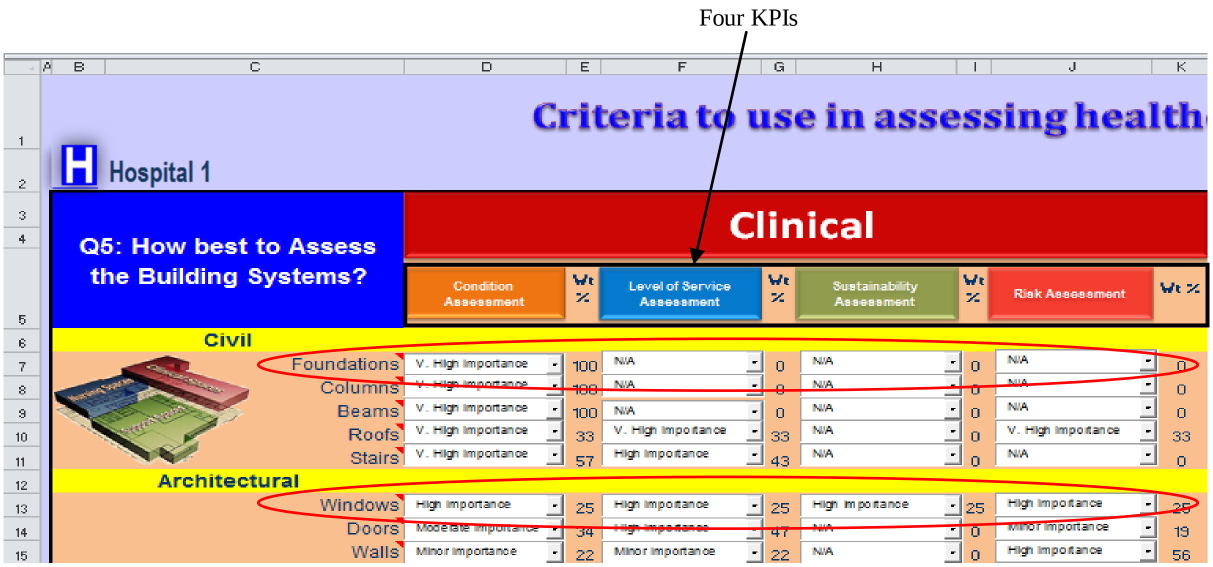
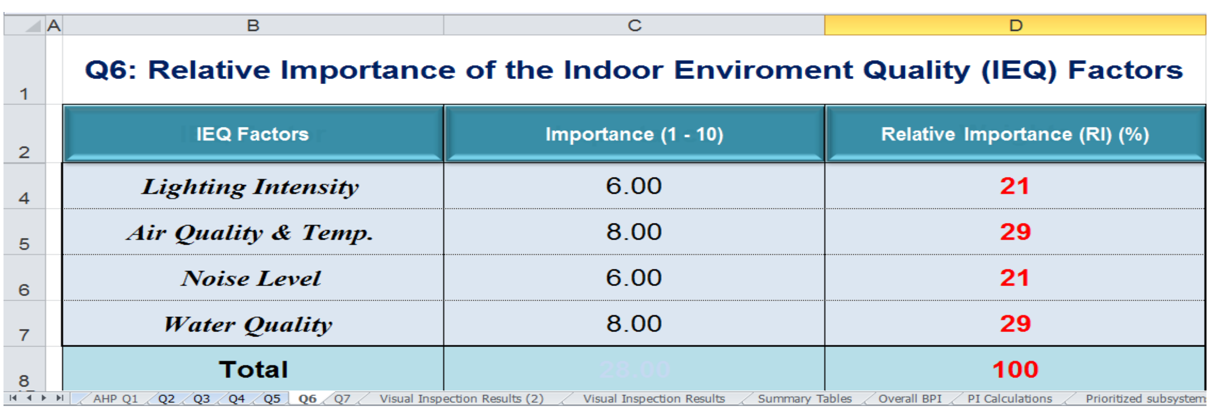


Figure 4.9: Applicability of the four KPIs to each subsystem

Figure 4.10 shows the "Q6 spreadsheet," which identifies the relative importance of each of the indoor environment quality (IEQ) factors that apply to the spaces in the hospital. The importance is defined on a scale from 0 (low importance) to 10 (high importance), and the relative importance is calculated accordingly, as shown in the right-hand column of Figure 4.10. Assessing the IEQ parameters for each space helps provide an evaluation of the LOS within each space and therefore of the subsystems that provide related services (air, water, light, and noise). For example, poor air quality in some spaces indicates a deficiency in the LOS of the HVAC system as a whole.



Q6: Relative Importance of the Indoor Enviroment Quality (IEQ) Factors

IEQ Factors	Importance (1 - 10)	Relative Importance (RI) (%)
Lighting Intensity	6.00	21
Air Quality & Temp.	8.00	29
Noise Level	6.00	21
Water Quality	8.00	29
Total	28.00	100

Figure 4.10: Relative importance of the IEQ factors

Figure 4.11 shows the “Q7 spreadsheet,” which identifies subsystems that are sensitive to the risk of failure. It also defines the possibility of a subsystem’s failure, the consequences of that failure, and the redundancy level for subsystems that involve risk. The level of redundancy is generally an indicator of a reduction in the overall risk, as discussed in Section 3.4.2. For example, the high-voltage switchgear subsystem has a double redundancy level, which means that two standby alternatives are available: standby generators and an additional source from the general grid. On the other hand, the nurse call system has no backup alternative.

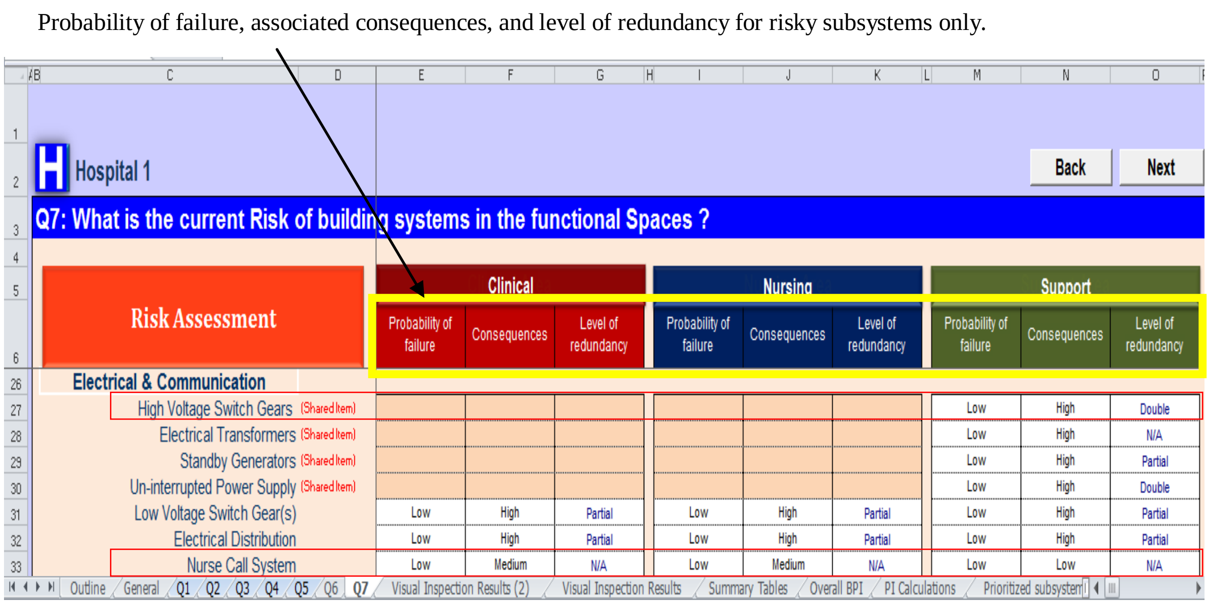


Figure 4.11: Probability of failure, consequences, and level of redundancy for risky subsystems

4.2.2 Part II of the survey: capital renewal practices

Part 2 of the survey questionnaire gathers data about the annual budget for regular maintenance and capital renewal work, the amount of backlog related to renewal work, the software used for supporting regular maintenance activities, inspection tools, the mechanism for allocating funds among the hospital components, the decisions that are most challenging for hospital maintenance, subsystems that entail the greatest risk, subsystems that are the most costly to maintain, and the cost of the renewal options for each subsystem, as shown in Table 4.1.

Table 4.1: Part II of the survey questionnaire

	Questions related to your Capital Renewal Practice
1	How much is the yearly budget for regular maintenance?
2	How much is the yearly budget for capital renewal work?
3	Are you experiencing a backlog in renewal work? Rough %______ Please explain:________________
4	What software do you use to support regular maintenance activities? CMMS system _________________ Spreadsheet_ Other: _________ (Please specify.)
5	Do you use software to organize emergency work orders? ________________ (Please specify.) Comment on the efficiency and benefits associated with the software: _________________________________
6	Do you use software to help with frequent visual inspection? Internal spreadsheet _____or Commercial___ Comment on its efficiency and the benefits derived:______________________________________. Does it allow visual assessment? Yes __ No_____ Does it take photos? Yes __ No ____ Other features:_____
7	What software do you use to allocate rehabilitation /renewal money to building components? (Please specify.)______________________
8	How do you prioritize the allocation of spending among various components (e.g., roofs vs. HVAC)? (Please specify.) ___________
9	What is the most challenging decision? Regular maintenance__Responding to emergency calls __ Inspection ____ Allocating renewal funds ____ Other ______________ Please explain: ________________
10	Which building components are most risky? _________________________ (Please specify.)

Table 4.1 (count.)

11	Do you have a list of emergency work orders for the last two years? Yes ___ No___ Can we access them? Yes___ No____
12	Are there government guidelines for renewal spending? ________________ (Please Specify).
13	Do you have your list of components and last inspection data, age, etc.? Yes__ No __Can we access? Yes __ No ___
14	Which items are the most costly to maintain? ____.
15	Which items deteriorate most quickly? ____.
16	In the table below, please identify the components that can be renewed by in-house maintenance staff, and the components that can be renewed only through contracts (outsourcing)?
17	In general, renewal work is performed approximately _____% in house + _____% through outsourcing.
18	What is the organizational chart for the maintenance/asset management department at the hospital?
19	Do you set targets for distributing your renewal funding? Civil:_%; Architectural: _%; Electrical & Communications: _%; Mechanical: _%; Equipment: %
20	What are the typical renewal options available for each building component?
21	Do you store the above data electronically? Yes____No____Can we access? Yes___No ____
22	Do you have historical renewal contract? Yes____No____Can we access? Yes___No ____

4.2.3 Case studies

Both parts of the survey questionnaire were used for the collection of real-life data from four general hospitals: two in Libya and two in Canada (the author could get access to). Table 4.2 shows general information about the hospitals, which have different sizes, levels of occupancy, and locations. The first two hospitals have high occupancy levels (i.e., more than 10 beds/1000 m2), while the last two have standard occupancy levels, as defined by Shohet (2003a).

In this study, data were collected through interviews with personnel from all four hospitals, but only the information about the first two was used for the field testing of the proposed framework.

Table 4.2: General information about the hospitals surveyed

General Information	Hospital 1	Hospital 2	Hospital 3	Hospital 4
Age (years)	38	93	61	60
Total covered area (m^2)	20,000	18,173	47,254	80,000
Number of beds	540	700	325	165
Level of occupancy /1000 m^2	27 (High)	38.52 (High)	6.88 (Standard)	2.05 (Standard)
Total annual budget (Canadian $)	26,307,692	23,076,923	70,000,000	255,000
Annual renewal budget (Canadian $)	5,261,538	461,538	10,000,000	152,000
Country	Libya	Libya	Canada	Canada
Use in this research	•Data collection •Visual inspection	•Data collection •Visual inspection	•Data collection	•Data collection

For all of the hospital case studies, three consecutive interview sessions were conducted; for part I of the survey, the interviews were with maintenance and construction professionals (e.g., Civil, Architectural, Mechanical, Electrical, and Communication). The first interview involved a meeting with two to four hospital professionals (maintenance and construction) in order to determine the relative importance of the hospital zones, the spaces included within each zone and their relative importance, IEQ factors, and the building systems and subsystems.

The second interview focused on determining the set of KPIs that apply to each subsystem, and the third interview was directed at collecting information about the annual budget for regular maintenance, the capital renewal process followed at the hospital, and the software typically used for maintenance activities and inspection assessment.

For Part II of the survey, all of the data were collected during one interview session with the maintenance experts. Based on both the Part I and Part II sessions, a variety of charts and tables were created and then used for the development and validation of the proposed framework. An analysis of the data collected is provided in the next subsection.

4.3 Data Analysis

This subsection introduces the analysis of the data collected from the interviews with maintenance experts at the hospitals surveyed, as represented by step 5 in Figure 4.1. To facilitate the comparison and analysis of the data, the information was summarized in tables and figures.

Table 4.3 shows the relative importance of the functional zones and related subsystems for all of the hospitals. All of the experts in all of the hospitals ranked the support zone (which includes all of the shared subsystems) as the zone with the highest importance (60 %), whereas the clinical zone and the nursing zone were graded at 20 % each. In terms of the systems, the electrical and communication, mechanical, and equipment systems were allocated the highest relative importance, followed by the architectural systems which vary greatly in their importance from one zone to another. Civil systems were assigned the lowest weights.

Table 4.3: Relative importance of zones and related systems

System	Hospital 1			Hospital 2			Hospital 3			Hospital 4		
	Clinical (20%)	Nursing (20%)	Support (60%)	Clinical (20%)	Nursing (20%)	Support (60%)	Clinical (20%)	Nursing (20%)	Support (60%)	Clinical (20%)	Nursing (20%)	Support (60%)
Civil	25	25	25	25	25	25	25	25	25	70	70	70
Architectural	90	90	40	90	90	40	90	70	40	70	70	70
Electrical & Communications	100	100	80	100	100	80	100	100	80	100	100	100
Mechanical	100	100	80	100	100	80	100	100	80	100	100	100
Equipment	100	N/A	80	100	0	90	100	N/A	90	100	N/A	100

Table 4.4 shows the relative importance of the spaces within the hospital using a scale from 0 (not important) to 10 (very important). Spaces in the clinical and nursing zones are generally assigned a high importance level, while spaces in the support zone area designated as having less importance, with the exception of the computer, electrical, mechanical, sterilization rooms and the renal. This discrepancy indicates that the level of service in these spaces should be high.

Table 4.4: Relative importance of functional spaces

Space	Zone	Hospital 1	Hospital 2	Hospital 3	Hospital 4
		RI*	RI	RI	RI
Operating Room	Clinical	10	10	10	Not obtained
Preparation Room	Clinical	9	9	9	Not obtained
X-Ray Room	Clinical	8	8	8	Not obtained
Assessment Room	Clinical	7	7	7	Not obtained
Patient Room	Nursing	8	8	8	Not obtained
Observation Room	Nursing	6	6	6	Not obtained
Nurse Station	Nursing	4	4	4	Not obtained
Computer Server	Support	9	9	9	Not obtained
Electrical Room	Support	9	9	9	Not obtained
Mechanical Room	Support	9	9	9	Not obtained
Sterilization Room	Support	9	9	9	Not obtained
Renal	Support	9	9	9	Not obtained
Change Room	Support	4	2	4	Not obtained
Mosque/Chapel	Support	2	2	2	Not obtained
Common Area	Support	6	2	6	Not obtained
Corridor	Support	2	2	2	Not obtained
Dictating Room	Support	2	2	2	Not obtained
Housekeeping	Support	4	2	4	Not obtained
Janitor Closet/Locker	Support	2	2	2	Not obtained
Bathroom	Support	6	2	6	Not obtained
Office	Support	6	2	6	Not obtained
Soiled Utility	Support	6	2	6	Not obtained
Staircase	Support	7	2	7	Not obtained
Storage	Support	7	2	7	Not obtained
Waiting Room	Support	4	2	4	Not obtained
Lounge	Support	2	2	2	Not obtained
Autopsy Room	Support	4	7	4	Not obtained
Cart/Can Washing	Support	7	7	7	Not obtained
Clean Linen	Support	5	3	5	Not obtained

Table 4.4 (count.)

Communication Station	Support	5	1	5	Not obtained
Conference Room	Support	4	1	4	Not obtained
Cooler/Freezer	Support	5	9	5	Not obtained
Lab	Support	8	8	8	Not obtained
Library	Support	3	1	3	Not obtained
Lobby	Support	4	4	4	Not obtained
Maintenance	Support	7	7	7	Not obtained
Kitchen	Support	8	8	8	Not obtained
Library	Support	3	1	3	Not obtained
Cafeteria/Retail Store	Support	2	2	2	Not obtained
Receiving	Support	7	7	7	Not obtained
Waste Room	Support	7	1	7	Not obtained

*RI=Relative importance

Table 4.5 shows the minimum acceptable condition for each system within each functional zone of each hospital. Civil and architectural systems generally have a greater margin of deterioration than the other three systems whereas the electrical, mechanical, and equipment systems have zero tolerance, especially in the clinical and nursing zones, an indication that these systems must operate without interruption (i.e., any failure may cost lives).

Table 4.5: Minimum acceptable condition for each system

System	Hospital 1			Hospital 2			Hospital 3			Hospital 4		
	Clinical (20%)	Nursing (20%)	Support (60%)	Clinical (20%)	Nursing (20%)	Support (60%)	Clinical (20%)	Nursing (20%)	Support (60%)	Clinical (20%)	Nursing (20%)	Support (60%)
Civil	70	70	70	70	70	70	70	70	70	60	60	70
Architectural	90	70	50	90	90	70	90	70	50	70	70	70
Electrical & Communications	100	100	90	100	100	90	100	100	90	100	100	100
Mechanical	100	100	90	100	100	90	100	100	90	100	100	100
Equipment	100	N/A	90	100	N/A	90	100	N/A	90	100	N/A	100

The relative importance of each subsystem and the associated KPIs for all hospitals are shown in Table 4.6 to Table 4.11. Table 4.6 shows the relative importance of each civil subsystem with respect to the civil system, along with the applicable KPIs. In general, all of the maintenance experts at all of the hospitals ranked the electrical, HVAC, medical gases, and fire protection subsystems as very important subsystems, and their KPIs (e.g., condition, LOS, and risk) were also evaluated as being very important. All experts considered the condition KPI to be the most important KPI for civil subsystems and the sustainability KPI to be the least important. Of the civil subsystems, the roofs and the stairs were considered to be the subsystems involving the greatest risk.

Table 4.6: Relative importance and KPIs related to civil subsystems

Subsystem	Hospital 1					Hospital 2					Hospital 3					Hospital 4				
	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk
Civil																				
Foundations	60	V	N/A	N/A	N/A	30	V	N/A	N/A	N/A	30	V*	N/A	N/A	N/A	60	V	N/A	N/A	N/A
Columns	60	V	N/A	N/A	N/A	30	V	N/A	N/A	N/A	30	V	N/A	N/A	N/A	60	V	N/A	N/A	N/A
Beams	60	V	N/A	N/A	N/A	30	V	N/A	N/A	N/A	30	V	N/A	N/A	N/A	60	V	N/A	N/A	N/A
Roofs	100	V	V	N/A	V	100	V	V	N/A	M	100	V	O	N/A	M	100	V	N/A	N/A	M
Stairs	100	V	H	N/A	N/A	100	V	M	N/A	M	100	V	N/A	N/A	M	100	V	N/A	N/A	M

**V = Very Important; H = Highly Important; M = Moderately Important; and O = Of Minor Importance*

Table 4.7 shows the relative importance and KPIs related to architectural subsystems. From the table, it can be seen that the windows and ceilings subsystems are the only ones that need to be assessed in terms of the four KPIs. In hospital 1, the façade subsystem has the least relative importance because the external façade of this hospital is made of marble, which mean that the experts at this hospital do not encounter maintenance problems with respect to this subsystem.

All of the experts at all four hospitals consider the floors subsystem to be very important and to be associated with a high risk level, as shown in Table 4.7. Interestingly, the relative importance of the parking and paved walkways is considered to be high at all hospitals because some experts consider these two subsystems to entail high risk for hospital users, and the user might sue in case of an accident. Other experts consider these subsystems to have a significant impact on the level of service.

Table 4.7: Relative importance and KPIs related to architectural subsystems

Subsystem	Hospital 1					Hospital 2					Hospital 3					Hospital 4				
	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk
Architectural																				
Windows	100	* H	H	H	H	100	M	M	H	O	100	M	M	H	O	60	M	M	H	O
Doors	100	M	H	N/A	O	100	M	M	N/A	H	60	M	M	N/A	H	60	M	M	N/A	H
Walls	30	O	O	N/A	H	30	O	O	N/A	O	30	O	O	N/A	O	60	O	O	N/A	O
Façade	30	M	N/A	N/A	M	100	M	O	M	O	60	M	O	M	O	60	M	M	M	O
Partitions	30	O	H	N/A	H	30	O	O	N/A	O	30	O	O	N/A	O	60	O	O	N/A	O
Floors	100	H	H	N/A	H	100	H	M	N/A	H	100	H	M	N/A	H	100	H	M	N/A	H
Ceilings	60	H	H	M	H	60	M	M	O	M	60	M	M	O	M	100	M	M	O	H
Signage	100	H	H	N/A	N/A	60	M	H	N/A	O	60	M	H	N/A	O	60	M	H	N/A	O
** Parking	100	V	V	N/A	O	100	V	V	N/A	O	100	V	V	N/A	O	100	V	V	N/A	H
** Paved Walkways	100	M	M	N/A	M	100	M	V	N/A	M	100	M	V	N/A	M	100	V	V	N/A	H
** Gardens	30	O	O	N/A	N/A	30	O	O	N/A	N/A	30	O	O	N/A	N/A	30	O	O	N/A	N/A
** Exterior lighting	100	H	H	N/A	H	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V

**V = Very Important; H = Highly Important; M = Moderately Important; and O = Of Minor Importance*
**** Shared subsystems have a Relative Importance (RI) = 1.25 of the above values.

The gardens were assigned the lowest level of importance for all of the hospitals surveyed, but the exterior lighting subsystem is given a high relative importance because it makes the surrounding area very bright at night and consequently improves the performance of the closed-circuit television (CCTV) subsystem.

Table 4.8 shows the relative importance and the KPIs related to electrical and communication subsystems. As indicated in the table, all of the experts at the four hospitals consider all electrical subsystems to be among the most important subsystems, and believe that their performance should be assessed in terms of three KPIs (condition, LOS, and risk) with equal levels of importance.

The experts at hospital 1 give the CCTV subsystem a high grade because they believe in the importance of this subsystem for indicating the arrival of maintenance engineers to perform renewal work on the medical gas valve; it previously failed and led to two deaths.

Maintenance experts in hospital 3 consider the master clock subsystem to be very important because it allows medical staff in the operating rooms, for example, to monitor the elapsed duration of anesthesia. Intercoms are not used in the first two hospitals.

Table 4.8: Relative importance and KPIs related to electrical and communications subsystems

Subsystem	Hospital 1					Hospital 2					Hospital 3					Hospital 4				
	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk
Electrical & Comm.																				
** High Voltage S.G.	100	* V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V
** Electrical Transf.	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V
** StdbyGener.	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V
** Un-int.Power S.	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V
L Voltage S.G.	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V
Electrical Distr.	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V
Nurse Call system	60	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V
Intercom system	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	60	M	M	N/A	M	60	M	M	N/A	M
Tel. system	100	V	V	N/A	V	100	H	V	N/A	V	100	H	V	N/A	V	100	H	V	N/A	V
Paging system	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	60	M	V	N/A	H	60	M	M	N/A	M
Closed-Circ. Tel.	100	O	O	N/A	H	N/A	N/A	N/A	N/A	N/A	60	O	O	N/A	O	30	O	O	N/A	O
Master Clock	60	O	O	N/A	O	N/A	N/A	N/A	N/A	N/A	100	O	V	N/A	V	60	O	O	N/A	O

**V = Very Important; H = Highly Important; M = Moderately Important; and O = Of Minor Importance*

****** Shared subsystems have a Relative Importance (RI) = 1.25 of the values above.

Table 4.9 shows the relative importance and the KPIs associated with the mechanical subsystems. As shown in the table, the experts in all four hospitals consider the water treatment plant to have a high level of importance because this subsystem provides purified water for the boilers, chillers, and medical devices, as well as for the hospital users. A sewage pump station is not used in either hospital 2 or hospital 3.

Hospital 2 uses split air-conditioning units for providing cooled air. The advantages of these separated units are minimal operation and maintenance costs, along with localized consequences of failure. This hospital also has only fire extinguisher cylinders not a complete fire system.

All of the experts at all four hospitals consider the elevators to be an important subsystem that provides a high level of service, and they thus rated the LOS KPI as very important. The medical gases subsystems were also universally included in the most important subsystems, with their performance to be assessed in terms of three KPIs (condition, LOS, and risk), all of which were assigned a very high importance level.

Experts in the hospital 1 gave the boiler low importance because the hot weather in Libya makes the need to the hot water can be postponed during the repair or renewal works.

Table 4.9: Relative importance and KPIs related to mechanical subsystems

Subsystem	Hospital 1					Hospital 2					Hospital 3					Hospital 4				
	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk
Mechanical																				
Water																				
Water treatment	100	H	H	H	H	100	H	H	H	H	100	H	H	N/A	H	100	H	H	N/A	H
Booster plant	100	H	H	N/A	H	N/A	N/A	N/A	N/A	N/A	100	H	H	N/A	H	100	H	H	N/A	H
Pipelines	100	V	V	M	V	100	V	V	M	M	100	V	V	M	M	100	V	V	O	O
Fixtures	60	V	V	O	V	100	V	V	O	O	100	V	V	O	O	100	V	V	O	O
Sewage																				
Sewage pmp st'n	100	H	H	M	H	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	30	H	H	V	M
Pipelines	100	O	H	O	H	100	O	H	O	O	100	O	H	O	O	100	H	M	H	O
Fixtures	60	O	H	O	H	100	O	H	O	O	100	O	H	O	O	100	H	M	H	O
HVAC																				
Chiller unit(s)	100	V	V	N/A	H	N/A	N/A	N/A	N/A	N/A	100	V	V	N/A	H	100	V	V	N/A	H
Boiler unit(s)	60	V	V	N/A	H	N/A	N/A	N/A	N/A	N/A	100	V	V	N/A	H	100	V	V	N/A	H
Coolant Towers	100	V	H	N/A	V	N/A	N/A	N/A	N/A	N/A	100	V	H	N/A	V	100	V	H	N/A	V
Air handling unit	100	V	H	N/A	H	N/A	N/A	N/A	N/A	N/A	100	V	V	N/A	M	100	V	V	N/A	H
Ducts/Diffusers	100	O	V	N/A	O	N/A	N/A	N/A	N/A	N/A	100	O	V	N/A	O	100	V	H	N/A	O
Fire protection																				
Pump (s)	100	V	V	N/A	V	N/A	N/A	N/A	N/A	N/A	100	V	V	N/A	V	100	V	V	N/A	V
Pipes& Valves	100	V	V	N/A	V	N/A	N/A	N/A	N/A	N/A	100	V	V	N/A	V	100	V	M	N/A	V
Fire detection	100	V	V	N/A	V	N/A	N/A	N/A	N/A	N/A	100	V	V	N/A	V	100	V	M	N/A	V
Elevators																				
Power cables	100	H	V	N/A	H	100	H	V	N/A	H	100	H	V	N/A	H	100	H	V	N/A	H
Mech. room	100	H	V	N/A	H	100	H	V	N/A	H	100	H	V	N/A	H	100	H	V	N/A	H
Medical gases																				
Source Equip.	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V
Pipelines	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	H	V
Valves	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	H	V
Compressor	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V	100	V	V	N/A	V

**V = Very Important; H = Highly Important; M = Moderately Important; and O = Of Minor Importance*

****** Shared subsystems has their Relative Importance (RI) =1.25 of the values above.

Table 4.10 shows the relative importance and related KPIs for equipment subsystems. As shown in the table, an MRI machine is not available in the first two hospitals, but it has been assigned a high relative importance by the experts at the last two hospitals. Its performance should be assessed in terms of condition, LOS, and risk. The relative importance of the CT scanner and X-ray equipment is considered high for all four hospitals.

Hospitals 3 and 4 do not have their own laundry services; all of this work is conducted outside the hospital in order to minimize the hospital's operational and maintenance costs.

Table 4.10: Relative importance and KPIs related to equipment

Subsystem	Hospital 1					Hospital 2					Hospital 3					Hospital 4				
	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk	Relative Importanc	Condition	LOS	Sustainability	Risk
Equipment																				
MRI	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100	V	V	N/A	H	100	V	V	N/A	O
CT scan	100	* V	V	N/A	H	100	N/A	N/A	N/A	N/A	100	V	V	N/A	H	100	V	V	N/A	O
X-ray	100	V	V	N/A	H	100	N/A	N/A	N/A	N/A	100	V	V	N/A	H	100	V	V	N/A	O
Kitchen	60	M	H	N/A	M	100	H	H	N/A	M	100	H	H	N/A	M	100	M	H	N/A	O
Laundry	60	M	H	N/A	M	60	M	H	N/A	M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

**V = Very Important; H = Highly Important; M = Moderately Important; and O = Of Minor Importance*

One of the unexpected findings of the survey is shown in Figure 4.12, which shows that the interviewees reported that an assessment of risk is needed for 91 % of the hospital subsystems, as opposed to the initial expected result of 5 %.

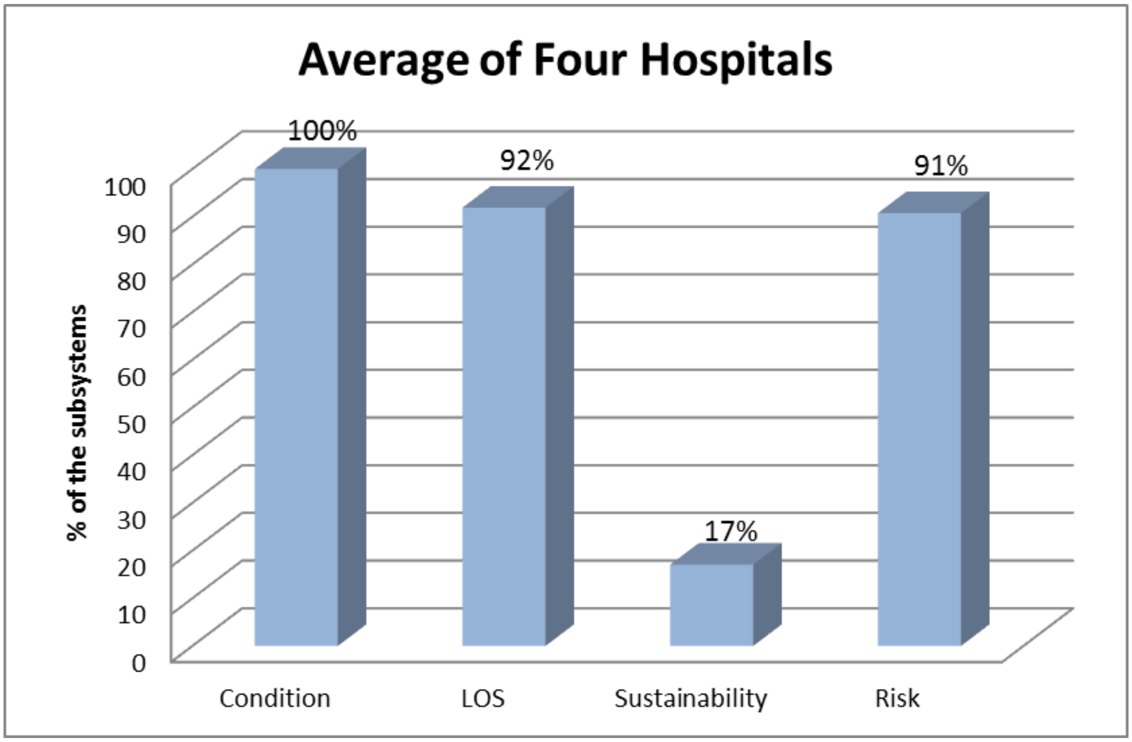


Figure 4.12: Percentage of subsystems for which each KPI applies

All of the maintenance experts ranked the electrical, HVAC, medical gases, and fire protection subsystems as high-risk subsystems because the malfunction of these subsystems has greater negative consequences than that of the architectural subsystems, as shown in Table 4.11. For example, the damage caused by the failure of the high-voltage switchgear will be more severe than that resulting from the failure of a door or window. The redundancy level (backup subsystems) for such subsystems is therefore double in order to minimize the risk of failure.

Table 4.11: Risk consequences associated with various subsystems

Subsystem	Hospital 1			Hospital 2			Hospital 3			Hospital 4		
	Probability	Consequences	Redundancy	Probability	Consequences	Redundancy	Probability	Consequences	Redundancy	Probability	Consequences	Redundancy
Civil												
Foundations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Columns	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Beams	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Roofs	L	H	N/A	L	H	N/A	L	H	N/A	L	H	N/A
Stairs	N/A	N/A	N/A	L	H	N/A	L	H	N/A	L	H	N/A
Architectural												
Windows	L	L	N/A	L	L	N/A	L	L	N/A	L	M	N/A
Doors	L	L	N/A	L	L	N/A	L	L	N/A	L	M	N/A
Walls	L	L	N/A	L	L	N/A	L	L	N/A	L	M	N/A
Façade	L	L	N/A	L	L	N/A	L	L	N/A	L	M	N/A
Partitions	L	L	N/A	L	L	N/A	L	L	N/A	L	M	N/A
Floors	L	L	N/A	L	L	N/A	L	L	N/A	L	M	N/A
Ceilings	L	L	N/A	L	L	N/A	L	L	N/A	L	M	N/A
Signage	N/A	N/A	N/A	L	L	N/A	L	L	N/A	L	L	N/A
Parking	L	L	N/A	L	L	N/A	L	L	N/A	L	H	N/A
Paved Walkways	L	L	N/A	L	L	N/A	L	L	N/A	L	H	N/A
Gardens	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Exterior lighting	L	M	Partial	L	M	Partial	L	M	Partial	L	H	Partial
Electrical & Comm.												
High Voltage Switchgear	L	H	Double	L	H	Double	L	H	Double	L	H	Double
Electrical Transformers	L	H	N/A	L	H	N/A	L	H	N/A	L	H	Double
Standby Generator	L	H	Partial	L	H	Double	L	H	Double	L	H	Double
Uninterrupted Power Supply	L	H	Double	L	H	Double	L	H	Double	L	H	Double
Low Voltage Switchgear	L	H	Partial	L	H	Partial	L	H	Partial	L	H	Partial
Electrical Distribution	L	H	Partial	L	H	Partial	L	H	Partial	L	H	Partial
Nurse Call System	L	L	N/A	L	M	N/A	L	H	N/A	L	H	N/A
Intercom System	N/A	N/A	N/A	N/A	N/A	N/A	L	L	N/A	L	L	N/A
Telephone System	L	H	Partial	L	H	Partial	L	H	Partial	L	H	Partial
Paging System	N/A	N/A	N/A	N/A	N/A	N/A	L	L	N/A	L	L	N/A
Closed-Circuit TV	L	L	N/A	N/A	N/A	N/A	L	L	N/A	L	L	N/A
Master Clock	L	H	Partial	N/A	N/A	N/A	L	H	Partial	L	L	N/A
Mechanical												
Water												
Water Treatment	L	H	N/A	L	H	N/A	L	M	Double	L	M	N/A
Booster Plant	L	H	N/A	L	H	N/A		N/A	N/A	L	M	Partial
Pipelines	L	H	Partial	L	H	Partial	L	H	N/A	L	H	N/A
Fixtures	L	H	Partial	L	H	Partial	L	H	Partial	L	H	Partial
Sewage												
Sewage Pump Station	L	H	N/A	N/A	N/A	N/A	N/A	N/A	N/A	L	H	N/A
Pipelines	L	H	N/A	L	H	N/A	L	H	N/A	L	H	N/A
Fixtures	L	H	N/A	L	H	N/A	L	H	N/A	L	H	Partial
HVAC												
Chiller Unit(s)	L	H	Partial	N/A	N/A	N/A	L	H	Double	L	H	Partial
Boiler Unit(s)	L	H	Partial	N/A	N/A	N/A	L	H	Double	L	H	Partial
Coolant Towers	L	H	Partial	N/A	N/A	N/A	L	H	Double	L	H	N/A
Air-Handling Unit	L	H	Partial	N/A	N/A	N/A	L	M	Partial	L	M	Partial
Ducts/Diffusers	L	H	N/A	N/A	N/A	N/A	L	L	N/A	L	L	N/A
Fire protection												
Pump (s)	L	H	Partial	N/A	N/A	N/A	L	H	Partial	L	H	Partial
Pipes& Valves	L	H	Partial	N/A	N/A	N/A	L	H	Partial	L	H	Partial
Fire Detection	L	H	Partial	N/A	N/A	N/A	L	H	Partial	L	H	N/A
Elevators												
Power Cables	L	H	N/A	L	H	N/A	L	H	N/A	L	H	Full
Mechanical Room	L	L	N/A	L	L	N/A	L	L	N/A	L	H	N/A
Medical gases												
Source Equipment	L	H	Partial	L	H	Partial	L	H	Partial	L	H	Partial
Pipelines	L	H	Partial	L	H	Partial	L	H	Full	L	H	Partial
Valves	L	H	N/A	L	H	N/A	L	H	N/A	L	H	N/A
Compressor	L	H	Full	L	H	Full	L	H	Partial	L	H	Full

Table 4.11 (coun.)

Subsystem	Hospital 1			Hospital 2			Hospital 3			Hospital 4		
	Probability	Consequences	Redundancy	Probability	Consequences	Redundancy	Probability	Consequences	Redundancy	Probability	Consequences	Redundancy
Equipment												
MRI	N/A	N/A	N/A	N/A	N/A	N/A	L	L	Full	L	L	Full
CT scanner	L	L	Full	N/A	N/A	N/A	L	L	Full	L	L	Full
X-ray	L	L	Full	N/A	N/A	N/A	L	L	Full	L	L	Full
Kitchen	L	L	Partial	L	L	Partial	L	L	Partial	L	L	Partial
Laundry	L	L	Partial	L	L	Partial	N/A	N/A	N/A	N/A	N/A	N/A

*High = 100; Medium = 70; Low = 40

Note: **Redundancy adjustment**: Partial = 50 %; Full = 10 %; Double = 2 %

Table 4.12 shows the relative importance of the IEQ factors for each hospital. Air quality and water quality factors are more important than lighting intensity and noise level because they have a more direct impact on the health of hospital users.

Table 4.12: Relative importance of IEQ factors

Indoor Environmental Quality (IEQ) Factors	Hospital 1	Hospital 2	Hospital 3	Hospital 4
Air quality & temperature	29	26	29	29
Water quality	29	29	29	29
Lighting intensity	21	23	21	21
Noise level	21	22	21	21
Total	**100**	**100**	**100**	**100**

4.4 Conclusions

This chapter has introduced the survey questionnaire that was used for gathering the data necessary for the development and validation of the proposed framework. The parts of the questionnaire were discussed separately, and the rationale behind each question was explained. Part I of the survey identified the relative importance of the main functional zones and spaces, systems, and subsystems, along with the applicable KPIs that best measure the performance of each subsystem and the relative importance of each KPI. Part II was also used to gather data from the maintenance departments with respect to the capital renewal practices applicable at the case study hospitals.

The data collected from the four general hospitals in the two countries were summarized in the form of tables and figures, and then analyzed. Based on the data analysis, some of the general findings are as follows: (1) the support zone is the most important zone (60 %), followed by the clinical and nursing zones (20 % each); (2) the subsystems that entail the greatest risk are the electrical, HVAC, medical gases, and fire subsystems; (3) the percentages of subsystems that should be evaluated in terms of the condition, LOS, sustainability, and risk are 100 %, 92 %, 17 %, and 91 %, respectively, and the relative importance levels of the quality of the indoor air, water, light, and noise are 29 %, 29 %, 21 %, and 21 %, respectively.

Chapter 5

Performance Assessment Case Studies

5.1 Introduction

This chapter provides details of the results of the performance assessment fieldwork carried out using the proposed framework for two of the hospital case studies: hospital 1 and hospital 2. The findings proved an effective mechanism for refining the proposed framework and validating its applicability for a healthcare environment.

5.2 Case Study 1 (Hospital 1)

This 38-year-old hospital is one of the largest in northeastern Libya. It was built in 1973 and then renewed in 2007. The hospital has a six-story main building, with a basement (mainly support services), ground floor (the remainder of the support spaces as well as clinical spaces), and four other floors (primarily nursing and support space), as detailed in Table 5.1. The hospital also includes other separate but linked facilities that house the boilers, chillers, water tank, coolant tower, parking, and gardens, as shown in Figure 5.1. The total area covered is 20,000 m^2 divided among the six floors, as indicated in Table 5.1. The hospital has 540 beds and serves a population of more than two million. In general, the occupancy level of this hospital is 27 beds/1000 m^2, which is high, according to Shohet (2003b).

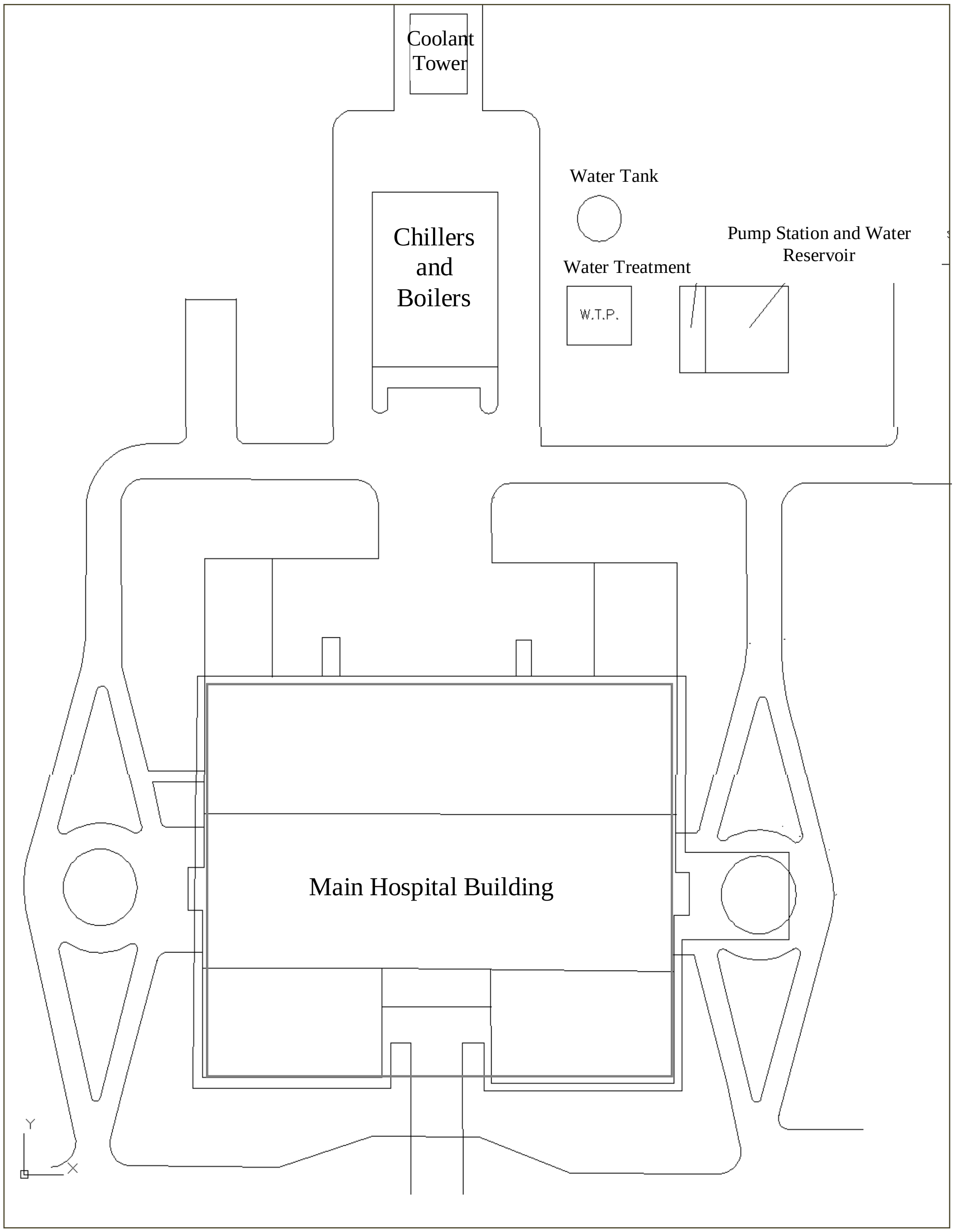


Figure 5.1: General layout of the hospital

Table 5.1: Floor areas, with number and type of spaces

Floor	Area (m2)	No. of Spaces	Clinical		Nursing		Support	
			m^2	%	m^2	%	m^2	%
Basement	5,194	138	388	7.5	__	__	4806	92.5
Ground	5,712	304	1382	24.2	90	1.6	4240	74.2
First	2,275	146	__	0.0	1024	45.0	1251	55.0
Second	2,269	146	__	0.0	1024	45.0	1245	55.0
Third	2,275	146	__	0.0	1024	45.0	1251	55.0
Fourth	2,275	146	__	0.0	1024	45.0	1251	55.0
Total	**20,000**	**1,026**	**1770**	**9**	**4186**	**21**	**14044**	**70**

5.2.1 Maintenance practice

The total annual budget of this hospital is reported as $26,307,692 (Canadian dollars) including the annual maintenance budget, which is $5,261,538 (Canadian dollars) (i.e., 20 %), as shown in Table 4.2. The hospital has a small maintenance department that is staffed by experts in a variety of fields (civil, mechanical, and electrical), that relies on limited resources, and that lacks both a computerized maintenance management system (CMMS) for maintenance purposes and software that can be used to prioritize subsystems for renewal plans. They also do not have a visual inspection application for assessing the physical condition of each subsystem. The maintenance engineers therefore experience significant difficulty obtaining the maximum benefit for the renewal funds available.

As shown in Table 5.2, in this hospital, all of the maintenance work for the civil and equipment systems is conducted by external contractors, 70 % of the maintenance work for the electrical and mechanical systems is performed by hospital maintenance staff, and 60 % of the maintenance work for the architectural systems is executed by external contractors. Overall, approximately 70 % of the renewal work is covered by the maintenance staff (in-house) and 30 % by contractors (outsourced).

Table 5.2: In-house versus outsourced component maintenance

System	In-house (70 %)		Outsourced (30 %)	
Civil		--------	100 %	All
Architectural	40 %	Carpentry, painting	60 %	Windows, plastering, brickwork
Electrical & Communications	70 %	External and internal lighting, low-voltage electrical work, switches	30 %	Transformers, exterior lighting, high-voltage switchgear
Mechanical	70 %	Chillers, boilers, water treatment, pump installation, HVAC	30 %	Elevators, repair of water pumps
Equipment		---------	100 %	CT scanner and X-ray

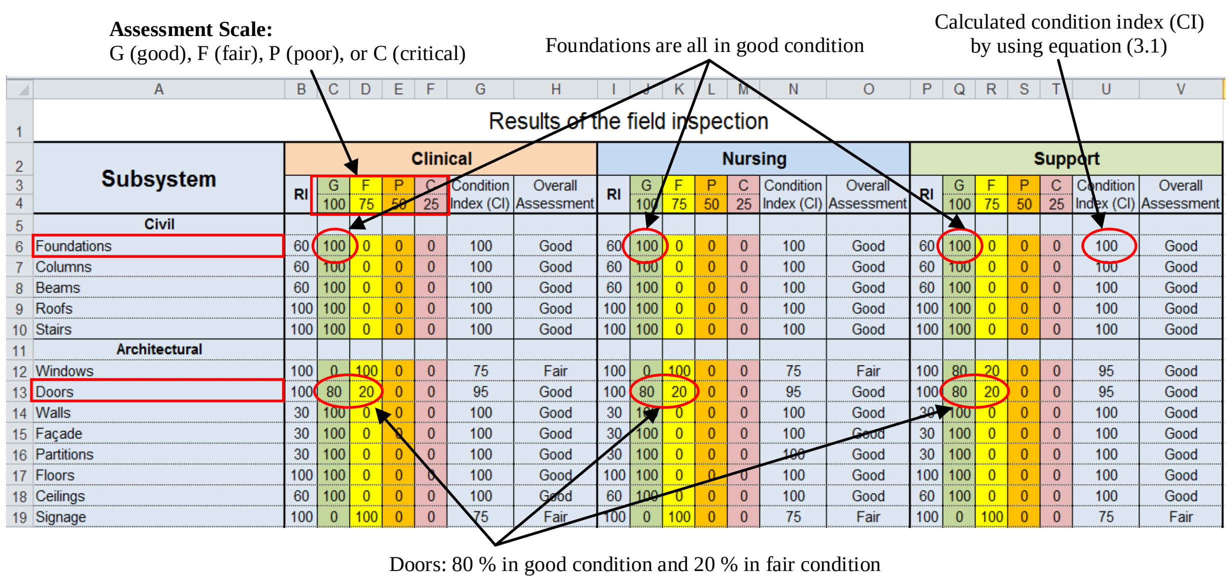
The maintenance department distributes renewal funding among the hospital systems approximately as follows: Civil, 5 %; Architectural, 10 %; Electrical and Communications, 30 %; Mechanical, 35 %; and Equipment, 20 %.

Based on the experience of the maintenance engineers at this hospital, the subsystems that entail the greatest risk are the medical gases and electrical systems, and the boilers and the generators are the most costly items to maintain due to the level of difficulty involved in their upkeep. The highest rate of deterioration is exhibited by the boilers and the chillers. Due to the hot Libyan environment and the consequent importance of cooling, the chillers have been assigned a higher priority than the boilers.

5.2.2 Visual inspection results

With the cooperation of two of the maintenance engineers, the developed visual inspection application was used for assessing both the physical condition of the subsystems and the indoor environment factors within the spaces. The overall assessment process for the all of the subsystems and spaces in the hospital building took about four hours, a shorter time than expected due to two factors: the benefit of the experience of the maintenance engineers, which enabled attention to be directed at less than adequate systems/subsystems, and the efficiency of the developed visual inspection application, which makes the assessment process both fast and productive.

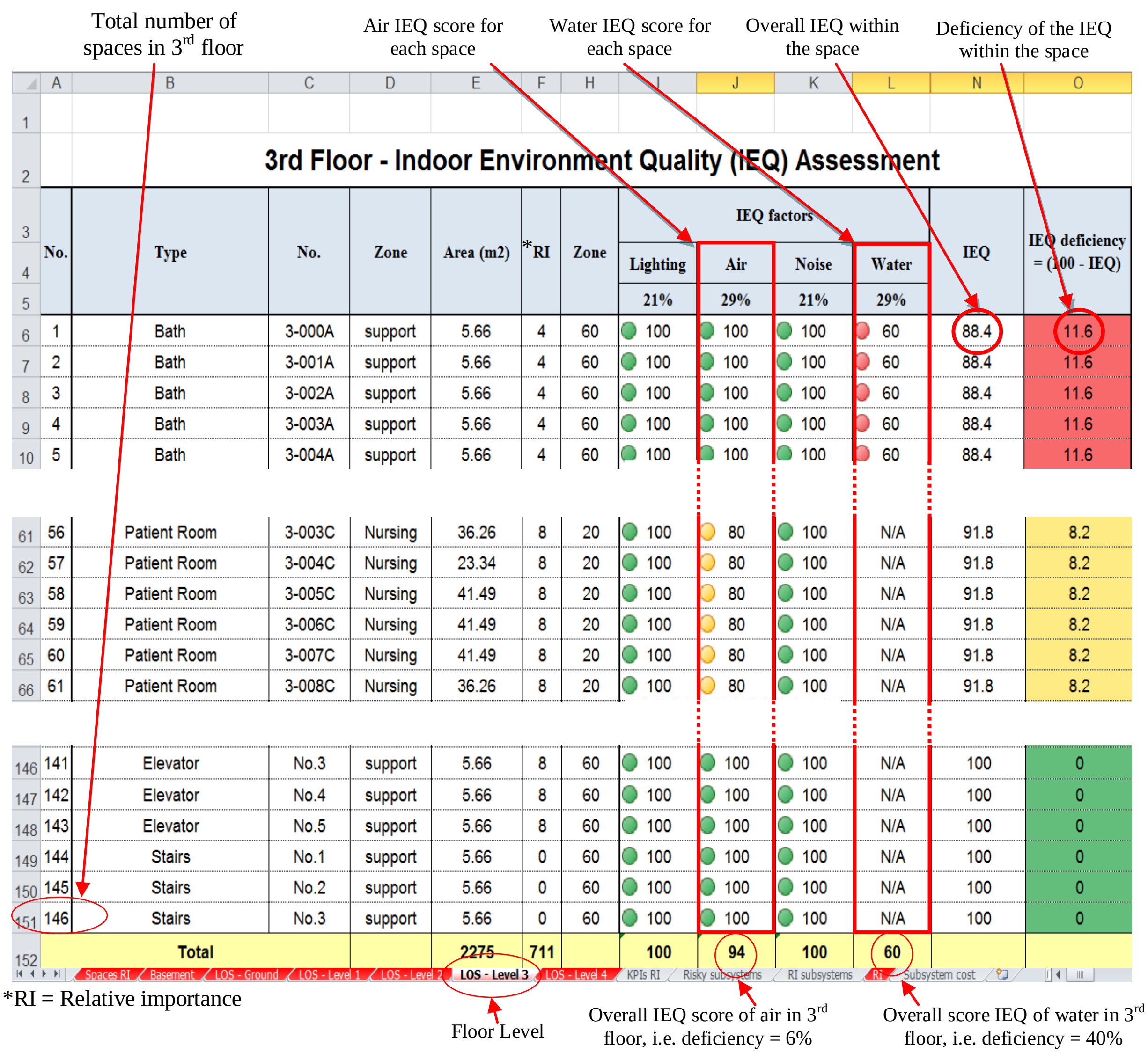
The physical condition assessment process employed a four-level scale (good, fair, poor, and critical), with poor indicating a score of 25, and good denoting a score of 100). The data collected were stored directly into an Excel spreadsheet, as shown in Figure 5.2. For example, the physical condition of the foundations in all functional zones is indicated as good (100 %), while the physical condition of 80 % of the doors is shown as good and of 20 % is fair; the overall assessment is thus 95 %, or good.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	Results of the field inspection																					
2	Subsystem	Clinical							Nursing							Support						
3		RI	G	F	P	C	Condition	Overall	RI	G	F	P	C	Condition	Overall	RI	G	F	P	C	Condition	Overall
4			100	75	50	25	Index (CI)	Assessment		100	75	50	25	Index (CI)	Assessment		100	75	50	25	Index (CI)	Assessment
5	**Civil**																					
6	Foundations	60	100	0	0	0	100	Good	60	100	0	0	0	100	Good	60	100	0	0	0	100	Good
7	Columns	60	100	0	0	0	100	Good	60	100	0	0	0	100	Good	60	100	0	0	0	100	Good
8	Beams	60	100	0	0	0	100	Good	60	100	0	0	0	100	Good	60	100	0	0	0	100	Good
9	Roofs	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good
10	Stairs	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good
11	**Architectural**																					
12	Windows	100	0	100	0	0	75	Fair	100	0	100	0	0	75	Fair	100	80	20	0	0	95	Good
13	Doors	100	80	20	0	0	95	Good	100	80	20	0	0	95	Good	100	80	20	0	0	95	Good
14	Walls	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good
15	Façade	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good
16	Partitions	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good
17	Floors	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good
18	Ceilings	60	100	0	0	0	100	Good	60	100	0	0	0	100	Good	60	100	0	0	0	100	Good
19	Signage	100	0	100	0	0	75	Fair	100	0	100	0	0	75	Fair	100	0	100	0	0	75	Fair

Figure 5.2: Portion of the physical condition results

The indoor environment quality (IEQ) assessment process was carried out only for the spaces that have problems. For example, 66 of the 146 spaces in the third floor of the hospital have a deficiency in the water system, parts of the assessment results for those spaces are shown in Figure 5.3, 5.4, and 5.5; the water quality is indicated (in yellow) as not good due to the corroded pipelines in this floor, and only 26 spaces in this floor (third floor) have air problems, as shown in Figure 5.3 and Figure 5.4.



3rd Floor - Indoor Environment Quality (IEQ) Assessment

No.	Type	No.	Zone	Area (m2)	*RI	Zone	IEQ factors: Lighting 21%	Air 29%	Noise 21%	Water 29%	IEQ	IEQ deficiency = (100 - IEQ)
1	Bath	3-000A	support	5.66	4	60	100	100	100	60	88.4	11.6
2	Bath	3-001A	support	5.66	4	60	100	100	100	60	88.4	11.6
3	Bath	3-002A	support	5.66	4	60	100	100	100	60	88.4	11.6
4	Bath	3-003A	support	5.66	4	60	100	100	100	60	88.4	11.6
5	Bath	3-004A	support	5.66	4	60	100	100	100	60	88.4	11.6
56	Patient Room	3-003C	Nursing	36.26	8	20	100	80	100	N/A	91.8	8.2
57	Patient Room	3-004C	Nursing	23.34	8	20	100	80	100	N/A	91.8	8.2
58	Patient Room	3-005C	Nursing	41.49	8	20	100	80	100	N/A	91.8	8.2
59	Patient Room	3-006C	Nursing	41.49	8	20	100	80	100	N/A	91.8	8.2
60	Patient Room	3-007C	Nursing	41.49	8	20	100	80	100	N/A	91.8	8.2
61	Patient Room	3-008C	Nursing	36.26	8	20	100	80	100	N/A	91.8	8.2
141	Elevator	No.3	support	5.66	8	60	100	100	100	N/A	100	0
142	Elevator	No.4	support	5.66	8	60	100	100	100	N/A	100	0
143	Elevator	No.5	support	5.66	8	60	100	100	100	N/A	100	0
144	Stairs	No.1	support	5.66	0	60	100	100	100	N/A	100	0
145	Stairs	No.2	support	5.66	0	60	100	100	100	N/A	100	0
146	Stairs	No.3	support	5.66	0	60	100	100	100	N/A	100	0
Total				2275	711		100	94	100	60		

*RI = Relative importance

Figure 5.3: Portion of the IEQ factor results

Air deficiency for the 3rd floor

Water deficiency for the 3rd floor

Floor	IEQ Deficiencies			
	Lighting (%)	Air Quality (%)	Noise (%)	Water (%)
Basement	0	0	0	0
Gorund	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	6	0	40
4	0	0	0	0
Overall deficiency	0	1	0	7

Air deficiency for the whole hospital

Water deficiency for the whole hospital

Figure 5.4: Water and air deficiencies for the third floor

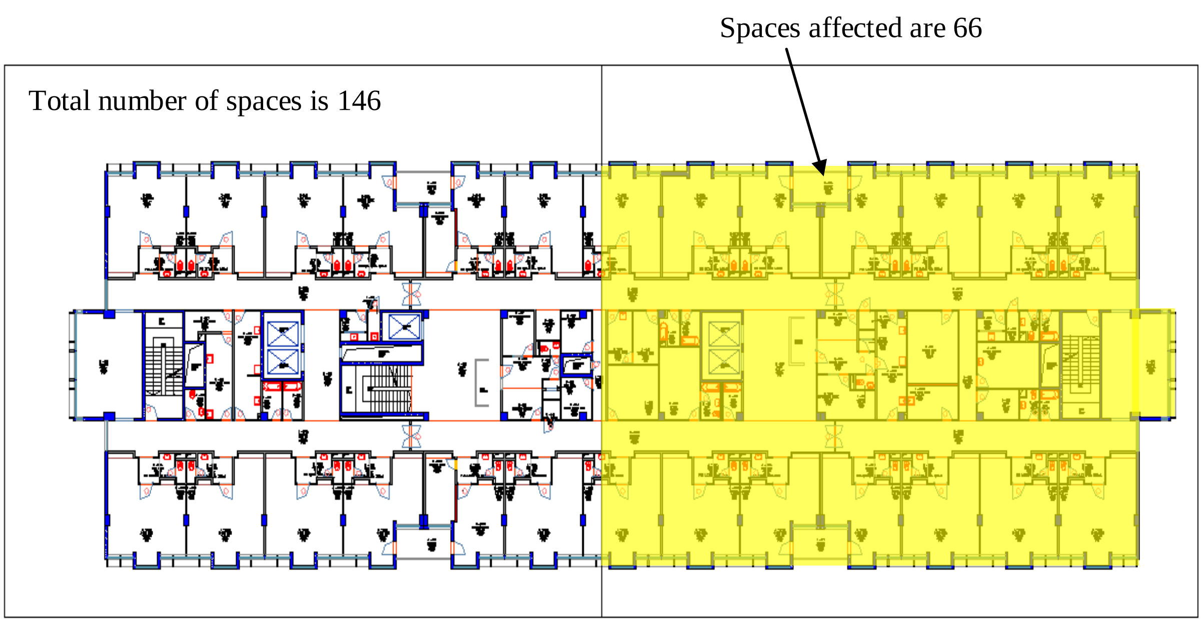


Figure 5.5: Locations of the spaces affected (water quality) in the third floor

During the visual inspection of the hospital building subsystems, observations were recorded about the current condition of the subsystems, as shown in Table 5.3.

Table 5.3: Visual inspection observations

Subsystem	Assessment/Observations	Photos
WATER TREATMENT PLANT	Hospital has two water treatment plants. One does not work and the other produces half of its productivity (i.e., does not cover the hospital demand). Both need renewal. Water treatment plant lacks purification filter and does not have a conductivity meter after the membrane. There is a lack of basic operational materials such as cotton filters.	
HVAC (Chillers & AHU)	Central air conditioning system contains four chillers, three of which are operating; the other needs maintenance. Air handling units (AHU): design error for the air intake vents, located on the ground level, led to the withdrawal the dust and dirt inside the unit, and thus speeded up the clogging of the filters. Mechanical room does not have a working extractor to pull out stale air and draw in fresh air.	
HVAC (Boilers)	One of the two boilers is not working and needs renewal. Chemical substances that are used to prolong the life of boilers and protect them from damage are lacking. There is a need for backup water pumps to supply the boilers with water. There is a need for backup fuel pumps to supply the boilers with fuel.	
SEWAGE PUMP STATION	This station needs renewal.	
MEDICAL GASES	An oxygen plant is needed in order to provide the hospital with the quantity of oxygen required in an emergency situation. A device for measuring the degree of purity of the medical oxygen is needed. Spare parts are lacking. Additional oxygen tank of 10,000 liter capacity has been installed to cover hospital demand during emergency situations.	

Table 5.3 (cont.)

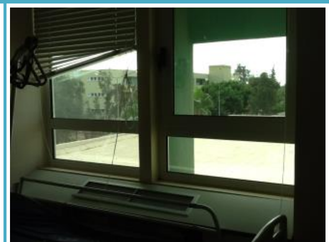
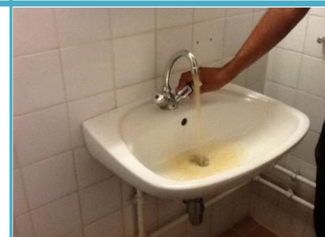
Subsystem	Assessment/Observations	Photos
WINDOWS	Due to the heavy weight of the window glass, some windows have failed.	
HIGH-VOLTAGE SWITCHGEAR	Existing transformers are insufficient to cover the full loads of the hospital: these transformers cannot run all HVAC equipment at the same time. The main switchboard needs to redistribute the loads. A voltage regulator should be installed to protect the medical devices in case of voltage fluctuations. For the most important departments, the uninterrupted power supply units should be replaced with new ones.	
ELECTRICAL DISTRIBUTION SYSTEM	The electrical distribution wires are incapable of carrying the hospital loads due to their poor design; therefore, all wires need to be replaced with ones that have a larger cross-section. The low-voltage switchgear board should also be replaced with a new one.	
ELEVATORS	Two of the five elevators do not work and need renewal work.	

Table 5.3(cont.)

Subsystem	Assessment/Observations	Photos
WATER PIPLINE SYSTEM	The main water pipeline is unable to cover the hospital's water needs. The lack of water purity has led to repeated breakdowns in the water treatment plant, which thus disrupts medical devices. The water pipeline network is corroded, which led to repeated diversions and a second pipeline explosion, resulting in damage to the hospital's medical devices.	

Details of the visual inspection of the hospital subsystems are as follows:

Water treatment plant: This unit is among the most important systems in the hospital building. For water to become fit for the desired end use, it is purified in the plant purifies through the removal of contaminants such as suspended solids, bacteria, viruses, and fungi, along with minerals such as iron, manganese, and sulphur. The existing water treatment plant includes two plants with a total production of 16,000 L/hr. One of these plants is not working and needs renewal, and the other produces only 7,000 L/hr (i.e., half of its productivity), a quantity that does not cover hospital demand. This shortfall in production is due mainly to the shortage of the productivity of the plants; shortage of chemicals, membranes, and spares. Both plants need renewal work because they have a profound effect on the boilers and the chillers, the functioning of which is dependent on purified water. Figure 5.6 shows some of the observations related to the water treatment plant. One of the most important factors is that the quality of the surrounding environment and utilities, for example, the quality of the water in the main city or area pipelines, has a significant impact on the age and life-cycle costs of the water treatment plant. An additional consideration is that the relative importance of this unit is high because it serves all hospital systems, devices, and end users. Any failure affects the functionality of other systems, such as boilers, chillers, and medical devices.

Figure 5.6: Low-capacity water treatment plant

HVAC: The central air conditioning system contains four chillers, three of which are operating; the other needs maintenance. Figure 5.7 reveals the poor design of the air handling units, in which the air intake vents are located at ground level, which could lead to the intake of dust and dirt inside the unit and thus speed up the clogging of the filters. This unit therefore needs to be relocated so that such design problems are resolved.

Figure 5.7: Problems in air handling units (AHU)

Boilers are also among the important subsystems of the HVAC system because they provide the hospital with hot water. The hospital has two boilers: one needs replacement, and the other cannot supply the hospital demand, as shown in Figure 5.8. In addition, an insufficient number of water pumps provide the boilers with water and need renewal. The pipelines of the coolant tower are also corroded and should be renewed, as shown in Figure 5.8.

Figure 5.8: Problems identified in the boilers, chillers, and coolant towers

Sewage pump station: The existing sewage pump station does not work properly and needs to be renewed, and a new sewage treatment plant is also required.

Medical gases: the medical gases system, generally, is essential for supplying the gases, such as oxygen, nitrogen, and medical air, through the pipes to various parts of the hospital, and this makes all its subsystems are very important. The main subsystems of the medical gases system are the pipelines, valves, compressors, and the source equipment, and this system is usually well monitored by a variety of computerized alarm systems so that the required precautions and measures can be implemented in order to avoid any consequences of the failure of any of the subsystems. For example, the blockage of a small valve due to impure oxygen led to two deaths. A resulting observation is thus that the hospital needs an oxygen plant to provide the hospital with the required quantity of pure oxygen so that such consequences can be prevented. As a temporary solution, a 10,000 liter oxygen tank has been provided to cover the hospital demand. Figure 5.9 shows photographs of the oxygen plant and the failed valve.

Figure 5.9: Problems with the medical gases system

Doors and windows: About 20 % of the hospital doors need lock and frame repairs, as shown in Figure 5.10. On the other hand, all of window frames need replacement due to the heavy weight of the glass panes.

Figure 5.10: Problems with doors and windows

High-voltage switchgear: The high-voltage switchgear is also among the most important systems because it provides power to all of the hospital systems. The high-voltage switchgear is usually connected from two different general electrical grid sources in order to guarantee a continuous power supply. The switchgear is also used for the control, protection, and isolation of the electrical equipment. The general condition of the high-voltage switchgear has deteriorated, and it needs to be renewed. In addition, the two existing standby generators are old and are incapable of supplying the loads required by the hospital subsystems, for example, the HVAC boilers and chillers, as shown in Figure 5.11.

Due to the poor ventilation of the room that houses the switchboard, the temperature rises inside the room and causes the switchboard to fail. The automatic main switch also fails to operate properly when power from the main network is restored.

Figure 5.11: Problems with the high-voltage switchgear subsystems

Low-voltage switchgear (electrical distribution): The electrical distribution wires are incapable of carrying the hospital loads due to their poor design; therefore, all of the wires need to be replaced with ones that have a larger cross-section. The low-voltage switchgear boards need to be replaced with new ones, as shown in Figure 5.12.

Figure 5.12: Problems with the low-voltage switchgear (electrical distribution)

Elevators: Elevators represent an important subsystem that provides transportation for food, patients, visitors, and medical staff to the hospital floors. The hospital has five elevators, two of which are not working and need to be renewed, as shown in Figure 5.13.

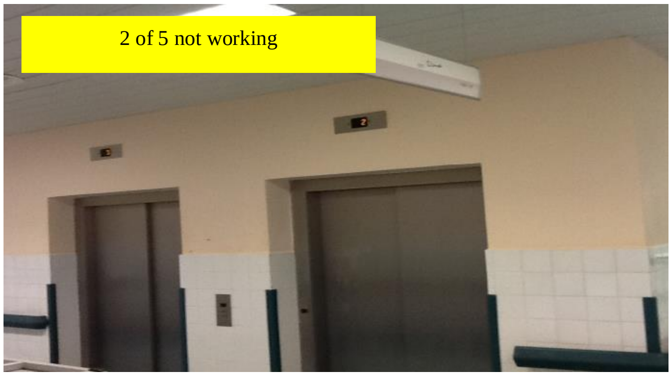


Figure 5.13: Elevator problems (2 of 5 not working)

Water pipeline systems: The main water pipeline is insufficient to provide the water supply required by the hospital. The lack of water purity has led to repeated breakdowns in the water treatment plant, with consequent disruptions to medical devices. The water pipeline network is also corroded, which has led to repeated diversions and pipeline explosions, events that sometimes damage medical devices. In some unoccupied levels of the building, such as levels 3 and 4, the pipelines are corroded and need to be replaced because these pipes have been left filled with water for long periods without use, as shown in Figure 5.14.

Figure 5.14: Poor water quality due to corroded pipelines

Pump house: The pumps in this house are among the most important subsystems because they draw water from the main pipeline and boost it to the storage tanks in order to cover the hospital demand and to compensate for any low flow from the main network. To provide a safe working environment for the maintenance staff, some general renewal work is needed for the pump house: internal lighting, electrical cables, and electrical boards. Figure 5.15 shows some of the subsystems that should be renewed.

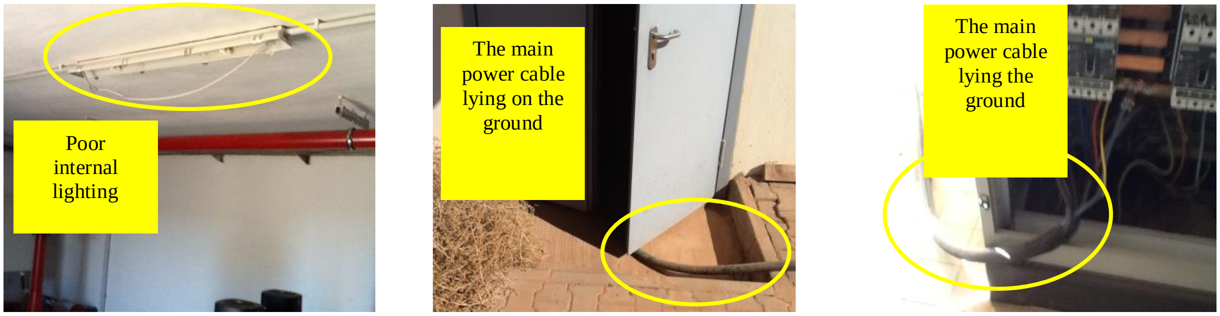


Figure 5.15: Problems with the pump house

Fire alarm system: The fire alarm is in good condition.

Figure 5.16: Fire alarm system

Parking and walkway pavement: The parking lot and paved walkways are in good condition and provide a high level of service.

Figure 5.17: Parking and paved walkways

5.2.3 Prioritization results

As indicated in Figure 5.18, based on the survey data and the visual inspection of the hospital subsystems and spaces, the overall subsystem importance (OSI), overall subsystem deficiency (OSD), and overall subsystem priority index (OSPI) were calculated, using the formulations discussed in section 3.4. A portion of the OSI calculation for each subsystem (row) is shown in Figure 5.18a, which is the product of the multiplication of the relative importance (RI) values for the subsystem, system, and zone. The calculation of the OSD and the OSPI are also shown in Figure 5.18b, where column I represents the visual inspection value of the condition index score obtained during the actual site visit to the hospital. Based on this value, the KPI deficiencies associated with each subsystem are calculated as shown in columns K, M, O, and Q: (100 − condition index score). The LOS deficiency indicated in column M is then modified according to the IEQ value obtained from the space inspection, and the risk deficiency value in column Q is also adjusted based on the level of redundancy determined during the inspection. The OSD is then calculated accordingly as the weighted sum of the KPI scores. Based on a comparison of the OSD values in column R with the minimum acceptable condition denoted in column S, a subsystem is designated eligible for renewal if the (100 − OSD) value is less than the minimum acceptable condition shown in column T. The end result is the prioritization of all the subsystems based on the OSPI values calculated, as shown in column U. For example, water treatment has the highest OSPI (3,850, column U) because it has the highest OSD (64, column R) and OSI (60, column H) values. On the other hand, in spite of a low OSI value of only 36, boilers are ranked third in priority (close to the top) due to their high deficiency level (44).

Subsystem importance

Subsystem priority

a) Calculation of the OSI

A	B	C	D	E	F	G	H
No.	**Subsystem**	**RI**	**System**	**RI**	**Zone**	**RI**	**Overall Subsystem Importance (OSI)**
1	Water Treatment - Support	125	Mech.	80	Support	60	60
2	Chiller Unit(s) - Support	125	Mech.	80	Support	60	60
3	Boiler Unit(s) - Support	75	Mech.	80	Support	60	36
4	Coolant Towers - Support	125	Mech.	80	Support	60	60
5	Sewage Pump Station (s) - Support	125	Mech.	80	Support	60	60
6	Electrical Transformers - Support	125	Elec. & Comm.	80	Support	60	60

Survey data

OSI x OSD = OSPI

b) Calculation of the OSD and OSPI

A	B	I	J	K	L	M	N	O	P	Q	R	S	T	U
No.	Subsystem	Visual assessment (Condition index)	Condition		LOS		Sustainability		Risk		Overall Subsystem Deficiency (OSD)	Comparsion with Minimum Acceptable Condition	Eligibility for renewal	Priority Index (OSPI = OSI x OSD)
			Wt.	Deficiency	Wt.	Deficiency	Wt.	Deficiency	Wt.	Deficiency				
1	Water Treatment - Support	38	0.25	63	0.25	69	0.25	63	0.25	63	64	(100-64)<90	Yes	3,850
2	Chiller Unit(s) - Support	63	0.36	38	0.36	38	0.00	38	0.27	19	33	(100-33)<90	Yes	1,964
3	Boiler Unit(s) - Support	50	0.36	50	0.36	51	0.00	50	0.27	25	44	(100-44)<90	Yes	1,567
4	Coolant Towers - Support	69	0.36	31	0.27	32	0.00	31	0.36	16	26	(100-26)<90	Yes	1,550
5	Sewage Pump Station (s) - Support	75	0.27	25	0.27	25	0.20	25	0.27	25	25	(100-25)<90	Yes	1,500
6	Electrical Transformers - Support	75	0.33	25	0.33	25	0.00	25	0.33	25	25	(100-25)<90	Yes	1,500

Subsystems

Visual inspection data

KPI deficiencies

Figure 5.18: Calculation of subsystem importance (OSI) and priority index (OSPI)

After the full priority list for capital renewal was generated, it was discussed with the maintenance staff at the hospital. The prioritized list of subsystems produced by the developed framework was compared with the list available at the maintenance department, which was part of their 2012 report prepared prior to the site visit; the results are shown in Table 5.4. In general, all of the subsystems that appear in the hospital's report also appear among the top 20 subsystems selected by the proposed framework. Although the prioritization produced by the framework is numerical and the hospital's report list is not, the two lists are a very close match.

Table 5.4: Comparison of the prioritization results produced by the framework and the maintenance department report

Prioritization results		
Developed framework	OSPI	**Maintenance department report**
Water Treatment - Support	3,850	Water Treatment
Chiller Unit(s) - Support	1,964	Chillers, Boilers, and Air Handling Units (AHU)
Boiler Unit(s) - Support	1,567	Sewage Pump Station
Coolant Towers - Support	1,550	*Medical Gases
Sewage Pump Station (s) - Support	1,500	Doors and windows
Electrical Transformers - Support	1,500	Electrical Transformers
Air Handling Unit - Support	1,293	Electrical Distribution
Sewage Pipelines - Support	1,200	Elevators
Water Pipelines - Nursing	1,038	
Un-interrupted Power Supply - Support	1,010	----
Electrical Distribution - Support	1,000	----
Low Voltage Switch Gear(s) - Support	1,000	----
Telephone System - Support	1,000	----
Closed-Circuit Television (CCTV) - Support	800	----
Sewage Fixtures - Support	720	----

(*) This subsystem has been renewed after two deaths in July 2012.

5.2.4 Overall building performance

As a continuation of the assessment calculations, the overall building performance index (OBPI) for this hospital was calculated based on the formulations presented in subsection 3.4.4 and was determined to be 90 %. Figure 5.19 shows a summary of the assessment results at the hospital level. The overall performance of the clinical, nursing, and support zones is 90 %, 86 %, and 92 %, respectively, which indicates good performance (i.e., greater than 70 %) (Shohet 2003a&b). The lowest performance is associated with the electrical, communication, and mechanical systems, whose levels vary from 80 % to 88 %, which are below 90 %. These deficiency values reflect the condition of important subsystems such as water treatment, chillers, boilers, the sewage pump station, electrical distribution, and transformers, all of which need renewal action in order to improve the overall building performance.

Overall Building Performance Index (OBPI)					90
Zone/System	Performance	Zone/System	Performance	Zone/System	Performance
Clinical	**90**	**Nursing**	**86**	**Support**	**92**
Civil	100	Civil	100	Civil	100
Architectural	91	Architectural	91	Architectural	95
Electrical & Comunications	80	Electrical & Comunications	80	Electrical & Comunications	84
Mechanical	88	Mechanical	84	Mechanical	86
Equipment	100	Equipment	N/A	Equipment	100

Figure 5.19: Overall building performance showing zones and systems

It should be noted that because the proposed framework includes predesigned spreadsheets for all calculations, the visual assessment visit required only four hours, and the associated results were then produced instantaneously. The hospital professionals very much appreciated this feature of the new system and consider it to be a major benefit.

5.3 Case Study 2 (Hospital 2)

This 93-year-old hospital is one of the oldest in northeastern Libya. Built in 1918, it includes 30 separate buildings (Figure 5.20), with a total area of 18,548 m^2 (Table 5.5). A total of 700 beds serve a population of more than two million. The general level of occupancy for this hospital is 38.52 beds/1000 m^2, which is high according to Shohet (2003b).

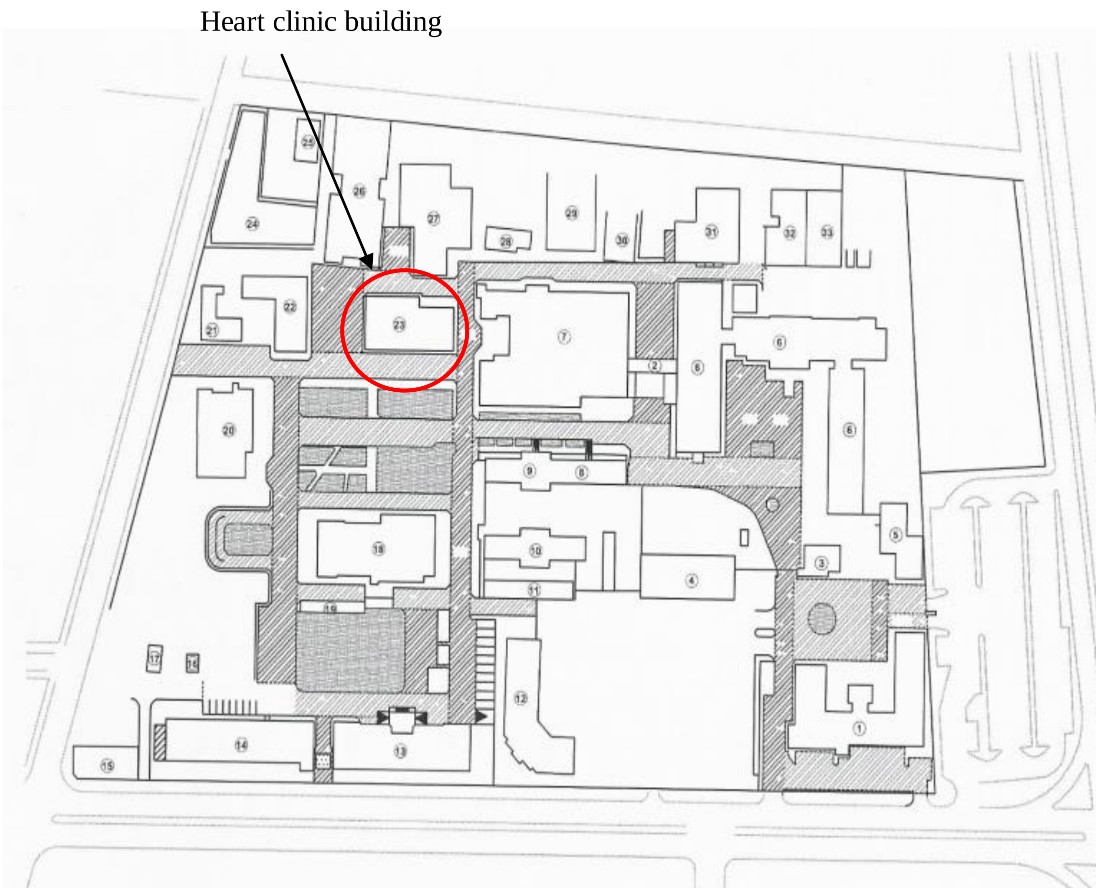


Figure 5.20: General layout of the hospital buildings

Table 5.5: Floor areas of the main buildings

No	Building	Floors	Area (m^2)	No	Building	Floors	Area (m^2)
1	Administration	Two	1,141.5	**16**	Nurses' Rooms	Two	393.75
2	Oncology Department	One	342.18	**17**	Dermatology	Two	899.25
3	Outpatient Clinics	One	687.08	**18**	Internal Medicine Dept.	Two	359
4	Library & Blood Bank	Two	524.21	**19**	Medical Staff Rooms	Four	458.66
5	Imaging & CT Scanner	One	479	**20**	Storage	One	951.63
6	Internal Medicine Dept.	One	201.06	**21**	Neurology	One	795.64
7	Reception	One	144.13	**22**	Gynecology	Two	1,956.25
8	Maternity	Three	940	**23**	**Heart Clinic**	**Two**	**981**
9	Maternity	One	661	**24**	Morgue	One	40
10	Reception	One	291	**25**	Maintenance Department	One	744.75
11	Maternity	Two	877	**26**	Hematology	Two	268.7
12	Laundry	One	691	**27**	Tissues	Two	394.88
13	Laboratory	One	478.8	**28**	Generators	One	35
14	Central Laboratory	Two	879	**29**	**Storage**	One	511
15	Kitchen	One	548.5	**30**	**Isolation Section**	Two	873.24
	Total				**18,548**		

One of the 30 hospital buildings is the heart clinic building, listed as building no. 23 in Table 5.5. This building was selected as a case study for the application of the developed framework. The building has two stories with a total of 981 m^2. The ground floor includes mainly support space (66 %), such as offices, storage, and baths, with 29 % taken up by clinical space, such as the intensive care unit and observation rooms. The first floor is comprised of support space (63 %), such as offices and baths, as well as nursing space and patient rooms (33 %), as shown in Table 5.6.

Table 5.6: Total floor areas and number of spaces in the heart clinic building

Floor	Area (m2)	No. of Spaces	Clinical		Nursing		Support	
			m^2	%	m^2	%	m^2	%
Ground	494	20	145	29	23	5	326	66
First	487	22	20	4	162	33	305	63
Total	**981**	**42**	**165**	**17**	**185**	**19**	**631**	**64**

5.3.1 Maintenance practice

The annual budget is reported as $23,076,923, which includes an annual maintenance budget of $461,538 (i.e., 2 %), as shown in Table 4.2. The hospital has a small maintenance department staffed by preventive and reactive experts in a number of fields. This department employs no computerized maintenance management systems (CMMS) nor does it have any software that can be used to prioritize subsystems for renewal plans. They employ paper forms and a digital camera for assessing the physical condition of each hospital subsystem. The department is dealing with a 60 % backlog in renewal work because of a limited budget and restrictive payment and contracting methods.

With respect to renewal work, approximately 40 % is usually performed by the maintenance staff (in-house) and 60 % by contractors (outsourced); the details are shown in Table 5.7. The department distributes renewal funding among the relevant systems approximately as follows: Civil, 5 %; Architectural, 25 %; Electrical and Communications, 30 %; Mechanical, 20 %; and Equipment, 20 %.

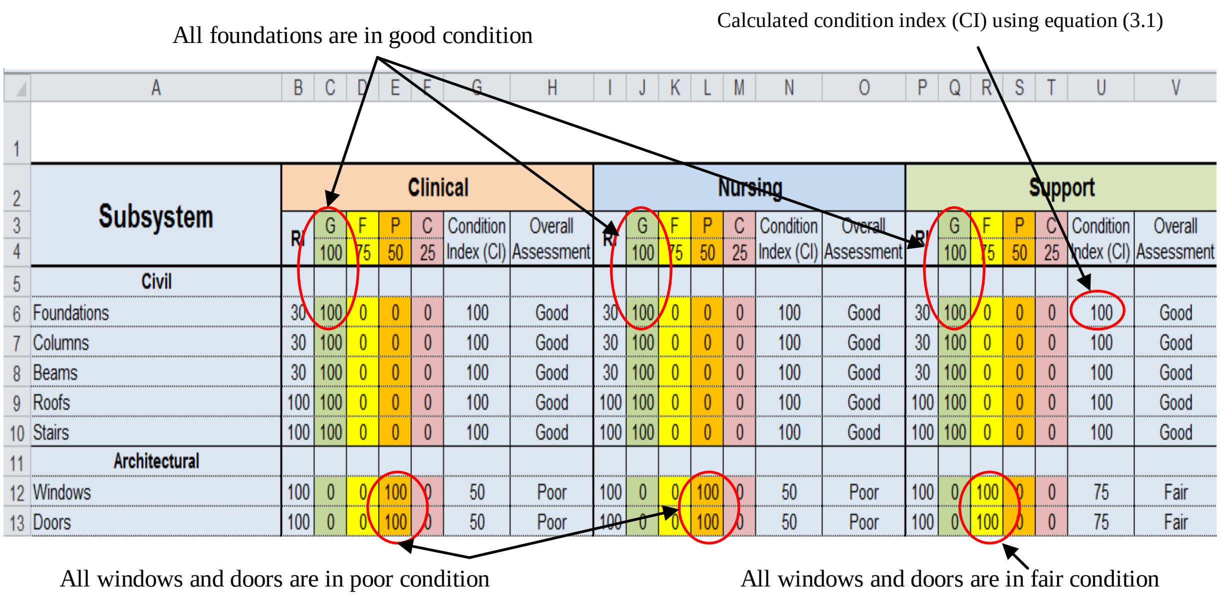
Table 5.7: In-house versus outsourced component maintenance

System	In-house		Outsourced	
	%	Work	%	Work
Civil	0	Nothing	100	All
Architectural	20	Carpentry, painting	80	Windows, plastering, brickwork
Electrical & Communications	40	External and internal lighting, low-voltage electrical works, switches	60	Transformers, External lighting poles, high voltage switch gear
Mechanical	80	Pumps, air conditioning, water fixtures, sewerage fixtures, etc.	20	Elevators, repair of water pumps, medical gases
Equipment	0	Nothing	100	CT scanner and X-ray

Based on the experience of the maintenance engineers at this hospital, the building subsystems associated with the greatest risk are the electrical works. The generators, elevators, and medical gases are the most costly items to maintain due to the difficulty involved in their upkeep. The highest rates of deterioration are exhibited by the lighting, electrical distribution fixtures, and water fixtures.

5.3.2 Visual inspection results

Three consecutive interview sessions were conducted with two of the maintenance professionals at the hospital. The developed visual inspection application was then used during a visual inspection that was carried out with the help of one of the maintenance engineers in order to assess the physical condition of the subsystems and the indoor environment quality factors within the spaces. The assessment results with respect to the physical condition of the building subsystems are shown in Figure 5.21, and the indoor environment factors are indicated in Figure 5.22.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1																						
2	Subsystem	Clinical							Nursing							Support						
3		R	G	F	P	C	Condition	Overall	R	G	F	P	C	Condition	Overall	R	G	F	P	C	Condition	Overall
4			100	75	50	25	Index (CI)	Assessment		100	75	50	25	Index (CI)	Assessment		100	75	50	25	Index (CI)	Assessment
5	Civil																					
6	Foundations	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good
7	Columns	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good
8	Beams	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good	30	100	0	0	0	100	Good
9	Roofs	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good
10	Stairs	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good	100	100	0	0	0	100	Good
11	Architectural																					
12	Windows	100	0	0	100	0	50	Poor	100	0	0	100	0	50	Poor	100	0	100	0	0	75	Fair
13	Doors	100	0	0	100	0	50	Poor	100	0	0	100	0	50	Poor	100	0	100	0	0	75	Fair

Figure 5.21: Visual inspection results: condition of the subsystems

Water deficiency in each space | Overall LOS within the space | Deficiency of the LOS within the space

Ground Floor - Indoor Environment Quality (IEQ) Assessment

Type	No.	Area (m2)	*RI	Zone	IEQ factors				IEQ	IEQ deficiency
					Lighting	Air	Noise	Water		
					21%	29%	21%	29%		
Intensive Care Unit (ICU)	G1	125	10	20	100	100	100	80	94.2	5.8
Bath 1	G1	5.5	6	60	100	100	100	80	94.2	5.8
Bath 2	G1	5.5	6	60	100	100	100	80	94.2	5.8
Bath 3	G1	5.5	6	60	100	100	100	80	94.2	5.8

*RI = Relative importance

Figure 5.22: Visual inspection results: indoor environment factors

During the visual inspection of the subsystems, observations were recorded about the current condition of the subsystems, as shown in Table 5.8.

Table 5.8: Visual inspection observations

Subsystem	Assessment/Observations	Photos
MEDICAL GASES	This system is very old and contains no device for measuring the degree of purity of the medical oxygen. Spare parts are lacking. An oxygen plant is needed in order to produce the amount of oxygen required at the hospital.	
SEWAGE	All sewage pipelines and fixtures need to be renewed.	

Table 5.8 (cont.)

WATER	All water pipelines and fixtures need to be renewed.	
FAÇADE	Due to the humidity, the façade needs renewal work. The humidity has penetrated to the internal faces of the walls.	
HVAC	Split units are used for providing rooms with cooled air and heating.	
DOORS	All doors and frames need replacement.	
ROOFS	Due to the humidity, some roof areas need minor renewal.	

Table 5.8 (cont.)

WINDOWS	The window frames are made of wood, have deteriorated, and need to be renewed.	
FLOORS	The floor tiles have deteriorated, and the whole floor needs to be renewed.	
ELEVATORS	All of the elevators are working.	

5.3.3 Prioritization results

Based on the survey data and the visual inspection of the hospital subsystems and spaces, the OSI, OSD, and OSPI were calculated as shown in Figure 5.23, using the formulations discussed in section 3.4. A portion of the OSI calculation for each subsystem (row) is shown in Figure 5.23a, which is the product of the multiplication of the RI values for the subsystem, system, and zone. The calculations of the OSD and the OSPI are also shown in Figure 5.23b, in which column I represents the visual inspection value of the condition index score obtained during the actual site visit.

Subsystem importance

Subsystem priority

a) Calculation of the OSI

No.	Subsystem	RI	System	RI	Zone	RI	Overall Subsystem Importance (OSI)
1	Medical Gases Source Equipment - Support	125	Mech.	80	Support	60	60
2	Medical Gases Valves - Support	100	Mech.	80	Support	60	48
3	Water Fixtures - Support	100	Mech.	80	Support	60	48
4	Water Pipelines - Support	100	Mech.	80	Support	60	48
5	Medical Gases Compressor - Support	125	Mech.	80	Support	60	60
6	Medical Gases Pipelines - Support	100	Mech.	80	Support	60	48
7	Sewage Pipelines - Support	100	Mech.	80	Support	60	48
8	Sewage Fixtures - Support	100	Mech.	80	Support	60	48

OSI x OSD = OSPI

b) Calculation of the OSD and OSPI

No.	Subsystem	Visual Assessment (Condition Index)	Condition		LOS		Sustainability		Risk		Overall Subsystem Deficiency (OSD)	Comparison with Minimum Acceptable Condition	Eligibility for Renewal	Priority Index (OSPI = OSI x OSD)
			Wt.	Deficiency	Wt.	Deficiency	Wt.	Deficiency	Wt.	Deficiency				
1	Medical Gases Source Equipment - Support	50	0.33	50	0.33	50	0.00	50	0.33	25	42	(100-42)<90	Yes	2,500
2	Medical Gases Valves - Support	50	0.33	50	0.33	50	0.00	50	0.33	50	50	(100-50)<90	Yes	2,400
3	Water Fixtures - Support	50	0.38	50	0.38	50	0.12	50	0.12	25	47	(100-47)<90	Yes	2,262
4	Water Pipelines - Support	50	0.32	50	0.32	50	0.18	50	0.18	25	46	(100-46)<90	Yes	2,187
5	Medical Gases Compressor - Support	50	0.33	50	0.33	50	0.00	50	0.33	5	35	(100-35)<90	Yes	2,100
6	Medical Gases Pipelines - Support	50	0.33	50	0.33	50	0.00	50	0.33	25	42	(100-42)<90	Yes	2,000
7	Sewage Pipelines - Support	75	0.18	25	0.45	25	0.18	25	0.18	25	25	(100-25)<90	Yes	1,200
8	Sewage Fixtures - Support	75	0.18	25	0.45	25	0.18	25	0.18	25	25	(100-25)<90	Yes	1,200

Subsystems

Visual inspection data

KPI deficiencies

Figure 5.23: Calculation of the OSI and OSPI

Based on this value, the KPI deficiencies associated with each subsystem are calculated as indicated in columns K, M, O, and Q: (100 − condition index score). The LOS deficiency specified in column M is then modified based on the IEQ value obtained from the space inspection, and the risk deficiency value in column Q is also adjusted according to the level of redundancy determined during the inspection. The OSD is calculated then accordingly as the weighted sum of the KPI scores. Based on the comparison of the OSD values in column R with the minimum acceptable condition in column S, a subsystem is designated eligible for renewal if the (100 − OSD) value is less than the minimum acceptable condition, as shown in column S. All of the subsystems are prioritized according to the calculated OSPI values, as indicated in column U. For example, the medical gases source equipment has the highest OSPI (2,500, column U) because it has the highest product resulting from the multiplication of the OSD (42, column R) by the OSI (60, column H). On the other hand, although it has a high OSI of 60, the medical gases compressor is ranked fifth in priority due to the low deficiency level of this subsystem (35).

5.3.4 Overall building performance

As shown in Figure 5.24, the OBPI of this hospital building is very low (52 %), with performance levels in the clinical, nursing, and support zones of 46 %, 61 %, and 50 %, respectively. Overall, the performance levels of the architectural, electrical and communication, and mechanical systems are the same as those of the clinical and nursing zones. The specific performance values for the architectural, electrical and communication, mechanical systems in all zones vary from 38 to 79, which are generally low and have a significant effect on the performance level of the building as a whole. Therefore, major renewal work for important subsystems such as medical gases, doors, windows, floors, water pipelines, and sewage pipelines and fixtures is needed in order to improve the overall performance of the building.

Overall Building Performance Index (OBPI)				52	
Zone/System	Performance	Zone/System	Performance	Zone/System	Performance
Clinical	**46**	**Nursing**	**61**	**Support**	**50**
Civil	100	Civil	100	Civil	100
Architectural	61	Architectural	61	Architectural	79
Electrical & Comunications	75	Electrical & Comunications	75	Electrical & Comunications	75
Mechanical	38	Mechanical	38	Mechanical	46
Equipment	0	Equipment	N/A	Equipment	0

Figure 5.24: Overall building performance, showing zones and systems

5.4 Conclusions

This chapter has presented the results of two real-life case studies conducted with the goal of validating the assessment and prioritization framework. Both case studies involved the implementation of the developed visual inspection application for assessing the physical condition of the subsystems and spaces. In the first case study, the overall performance of hospital 1 is 90 %, and the subsystems designated for renewal include water treatment, chillers, boilers, the sewage pump station, electrical distribution, and transformers. A high degree of correlation is evident between the prioritization list produced by the framework and the list prepared by the hospita1maintenance department. In the second hospital case study, the overall performance is defined as very low (52 %) due to the poor performance of its architectural, electrical, communication, and mechanical systems, as evidenced by the major rehabilitation required in important subsystems such as medical gases, doors, windows, floors, water pipelines, and sewage pipelines and fixtures. These two case studies demonstrate the functionality of the proposed framework and highlight the reduced effort required to produce the results, benefits that were greatly appreciated by the hospital maintenance experts.

Chapter 6

Capital-Renewal Optimization

6.1 Introduction

This chapter introduces the capital-renewal optimization model, which integrates deterioration modeling, consideration of the type of renewal, performance improvement models, and life cycle cost analysis (LCCA). Using two different objective functions, the model was applied for the hospital 1 case study. The fund allocation results are presented and explained, along with the details of the model and the flexible options for its application.

6.2 Capital-Renewal Optimization Model

The model developed for optimizing capital-renewal fund allocation is a comprehensive LCCA model that integrates the performance assessment model presented in previous chapters with other important functions, as shown in Figure 6.1. All of these functions have been implemented within an integrated spreadsheet model that incorporates all of the equations related to the individual functions; in addition to macro programs developed using the Excel Visual Basic for Applications programming language for the application of the optimization process. Each subsystem is represented as a separate row in the spreadsheet model, and data are recorded in the columns. The model illustrated in Figure 6.1 has been formulated to include a five-year planning horizon for the capital renewal plan. The two main output components to be determined by the model are an index that designates one of the five renewal years, as indicated in column X for each subsystem, and an index for one of four renewal types, to be listed in column Y for each subsystem. For each subsystem, these two decisions together represent when and how each subsystem will be renewed within the planning years. The description of the various functions and their implementation in the spreadsheet model are discussed in the following subsections.

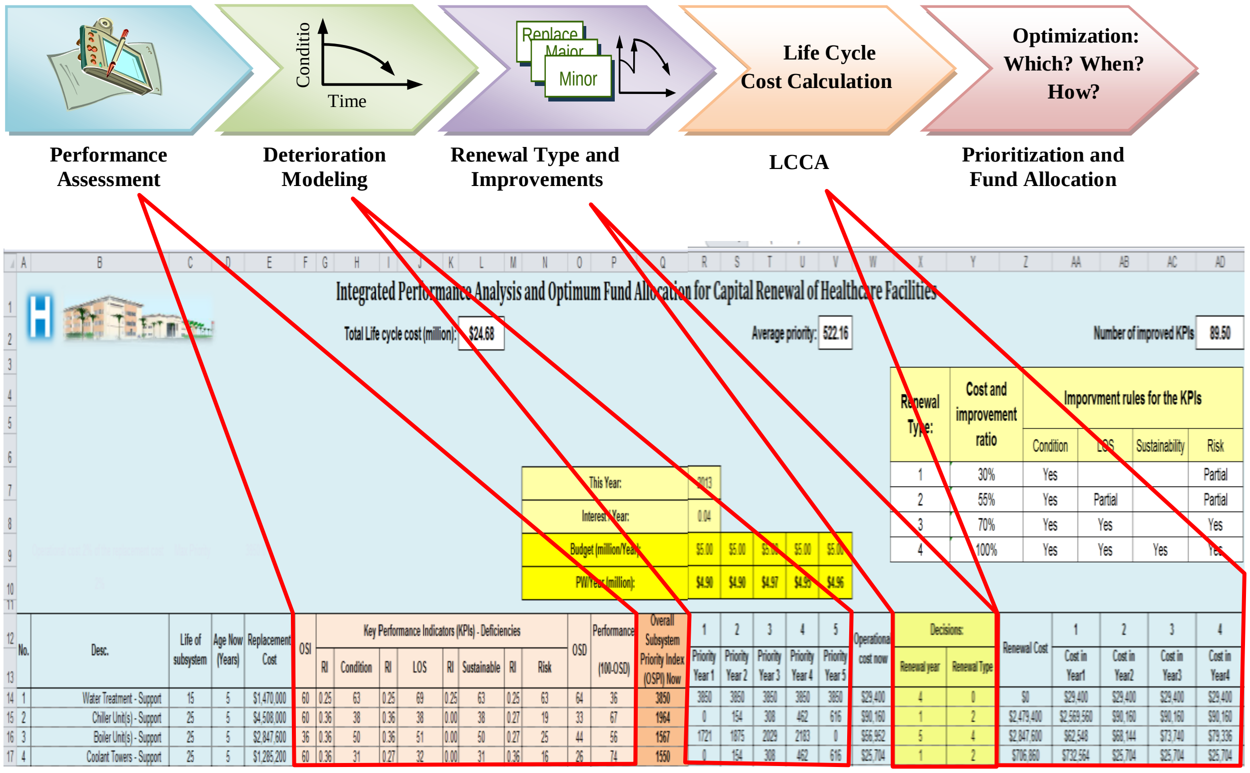


Figure 6.1: Capital-renewal optimization model, with main asset management functions

6.2.1 Performance assessment

The performance assessment function relates to the multiple-criteria deficiency calculation discussed in Chapter 5. The calculations for determining the condition, LOS, sustainability, and risk deficiencies are shown in columns H, J, L, and N of Figure 6.2, respectively, and in Table 6.1. These four performance criteria for each subsystem are combined as a measure of the overall subsystem deficiency (OSD), indicated in column O.

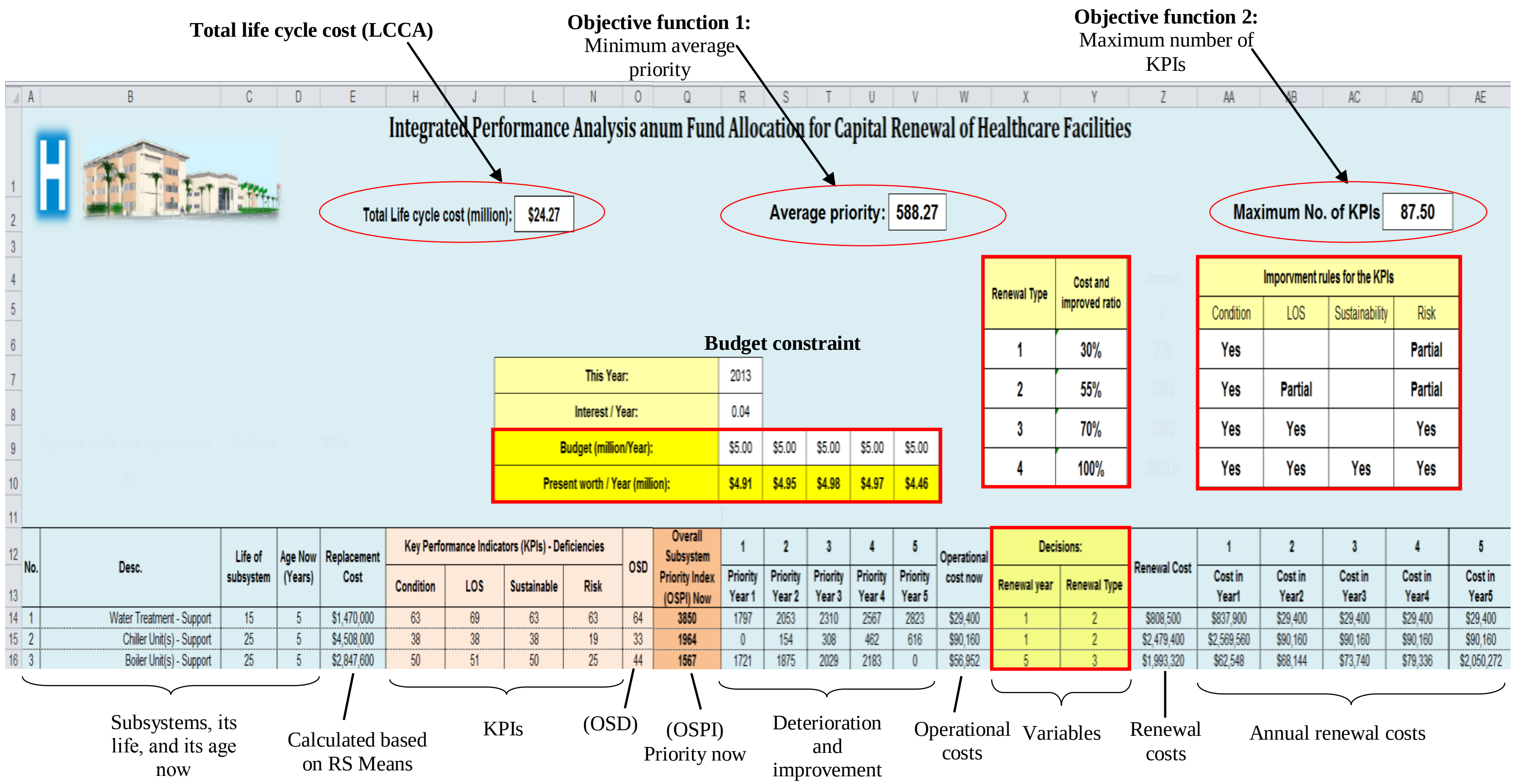


Figure 6.2: Main features of the capital-renewal optimization model

Table 6.1: Details of the spreadsheet model

Column	Description	Note
A	Serial number of the subsystem	
B	Subsystem name	
C	Life of the subsystem in years	
D	Current age of the subsystem in years	5 years since the last overall renewal of the hospital (2007)
E	Replacement cost of the subsystem in Canadian dollars	Calculated based on the RS Means costs
F	Overall subsystem importance (OSI) as a percentage	Calculated based on subsection 3.4.1 and Figures 3.9 and Figure 6.1
G, I, K, & M	Relative importance of the applicable KPIs	Expert input - Figure 6.1
H, J, L, & N	The deficiencies according to the KPIs applied	Field inspection
O	The overall subsystem deficiency (OSD)	Calculated based on subsection 3.4.2 and Figures 3.9 and Figure 6.1
Q	The overall subsystem priority index (OSPI) based on current value	Calculated based on subsection 3.4.3 and Figure 3.9
R, S, T, U, &V	The annual priority for five-year plan	Calculated based on equation (6.2)
W	The operational cost of the subsystem	Assumed to be 2 % of the replacement cost of the subsystem
X	Renewal year (variable from 1 to 5)	To be identified by the optimization (GA)
Y	Renewal type (Variable from 1 to 4)	To be identified by the optimization (GA)
Z	Renewal cost in Canadian dollars	Percentage of the replacement cost that is dependent on the renewal type selected
AA, AB, AC, AD, & AE	The annual costs of each subsystem	Calculated based on subsection 6.2.4

The overall subsystem priority index (OSPI) is then calculated, as shown in column Q. It should be noted that a subsystem with an OSPI value of zero indicates that its performance level is high: the subsystem has a low renewal priority. On the other hand, a subsystem that has a high OSPI value will also have a high priority for renewal. For example, water treatment has the highest priority because it has the highest OSPI value (3850), as shown in column Q of Figure 6.2. On the other hand, the boiler has a lower priority because its OSPI is only 1567. Based on the OSPI values, the future performance of the subsystem can be predicted using a deterioration model and the renewal decision, as explained in the following subsection.

6.2.2 Deterioration modeling

Prediction of the future performance of a subsystem is an important component of LCCA over a five-year planning period. A deterioration model has therefore been used as a means of estimating the future decline in the performance of a subsystem (i.e., the increase in the OSPI value) over time. As shown in Figure 6.2, in the developed model, a linear deterioration model has been applied to all subsystems because of its simplicity and because of the absence of historical data related to hospital components. In the model, the OSPI deteriorates each year by a rate equal to (1/expected life).

The OSPI in each year is therefore calculated using Equation 6.1, based on the linear deterioration behaviour and also on the consideration of any renewal strategy to be applied for any year, as follows:

$$OSPI_i = OSPI_{i-1} + \text{Scale x } (1/\text{ expected life of subsystem}) - RI_i \quad (6.1)$$

where $OSPI_i$ = Overall subsystem priority index for the current year

$OSPI_{i-1}$ = Overall subsystem priority index for the previous year

Scale = Maximum possible deterioration = 3850

RI_i = Improvement due to the renewal decision for that year

As an example, Figure 6.3 shows the method for calculating the annual priority index for water treatment (first subsystem listed in Figure 6.2) using equation (6.1), as follows:

Priority index for water treatment in year 1 (i = 1):

$OSPI_{now}$ = 3850 (column Q)

$OSPI_1$ = 3850 + 3850 (1/15) – 2310 (improvement due to renewal type 2 in year 1, discussed later)

$OSPI_1$ = 1,797 (as shown in Figure 6.3)

Priority index for water treatment in year 2 (i = 2):

$OSPI_2$ = 1,797 + 3850 (1/15) – 0 (i.e., no renewal in this year) = 2,053 (as shown in Figure 6.3)

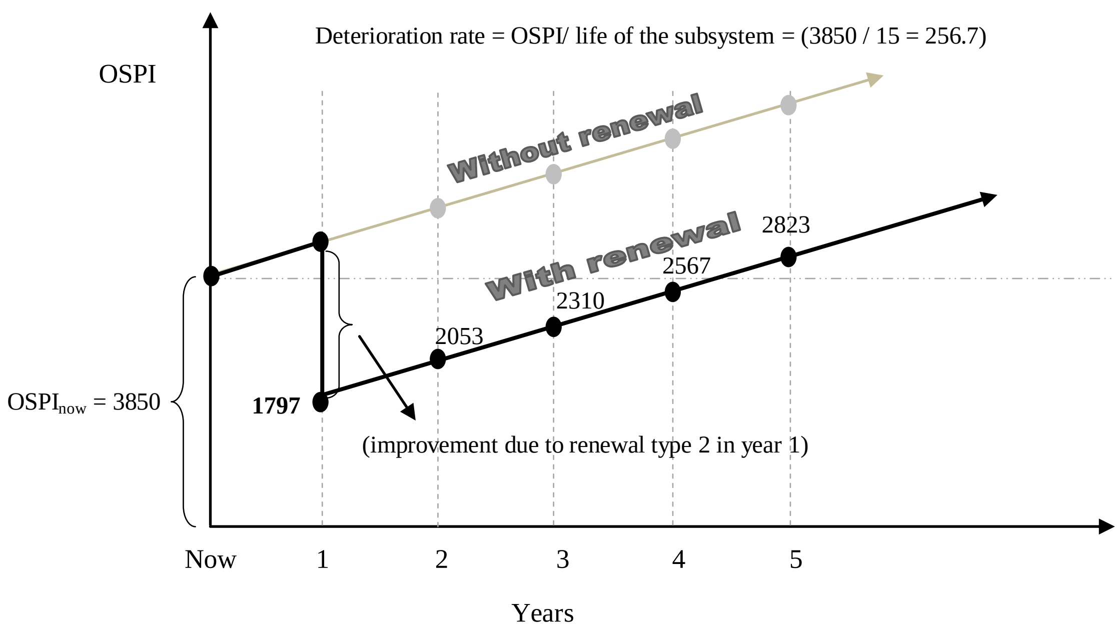


Figure 6.3: Calculation of the annual priority (water treatment)

These calculations are repeated for years 3, 4, and 5. The results are shown in Figure 6.2, and the impact of a variety of renewal decisions is represented schematically in Figure 6.4.

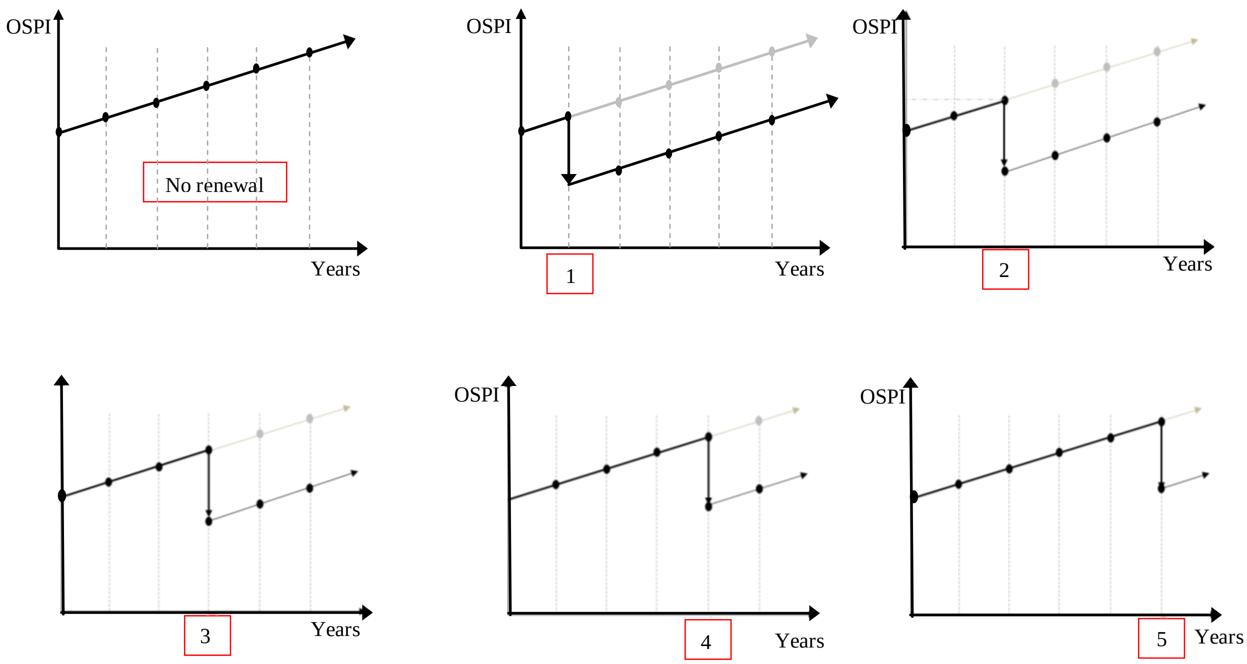


Figure 6.4: Performance under different renewal decisions

6.2.3 Renewal type and condition improvement model

The developed model includes four renewal options for each subsystem. They vary from minor renewal (type 1) to full replacement (type 4), as shown in Figure 6.5. The cost of each renewal type as a percentage of the full replacement cost is shown in Figure 6.5 (user input) along with the expected improvement in performance provided by each renewal type with respect to priority and also to the KPIs. For example, renewal type 1 costs 30 % of the total subsystem replacement cost, as shown in column E of Figure 6.2, and it improves the OSPI of the renewed subsystem by 770 points (30 % of the maximum scale of 3850). To differentiate among the different types of renewal options, the value of their impact on the overall performance (Column Y Figure 6.5) varies considerably. To reflect the improvement in the specific KPIs that apply to each subsystem, a few simple rules have been assumed, as shown in columns AA, AB, AC, and AD of Figure 6.5. For example, it is assumed that renewal type 1 leads to improvement in the condition and also partially in the amount of associated risk. Therefore, renewal type 4 (i.e., full replacement) will improve all four types of KPIs as well as the performance of the subsystem: the more expensive the renewal type applied or selected, the greater the benefit and increased performance level obtained.

X	Y	AA	AB	AC	AD
Renewal Type	**Cost and improvement ratio**	**Improvement rules for the KPIs**			
		Condition	LOS	Sustainability	Risk
1 (minor)	30%	Yes			Partial
2 (medium)	55%	Yes	Partial		Partial
3 (major)	70%	Yes	Yes		Yes
4 (full replacement)	100%	Yes	Yes	Yes	Yes

Figure 6.5: Renewal types, their cost percentages, and the improvement provided

Similarly, other renewal types are assumed to affect different KPIs, with full replacement improving all KPIs together. These rules can be changed by the user and can be beneficial for the later optimization of the level of fund allocation for creating improvements with respect to specific KPIs.

6.2.4 Life cycle cost calculation

The developed model has the capacity to calculate the life cycle cost for each subsystem over a five-year plan, including consideration of both the operational and the renewal costs associated with each renewal year as well as the type of renewal decision, as indicated in columns X and Y of Figure 6.2. The corresponding annual costs are shown in columns AA, AB, AC, AD, and AE for each respective year of the five-year plan. The evaluated cost portion of Figure 6.2 is shown in Figure 6.6. The annual renewal costs are calculated as follows:

(Total cost) = (Renewal cost + Operational cost) (6.2)

As an example, Figure 6.6 shows the annual costs for the water treatment subsystem for five years, given a decision of a year 1 renewal year and a type 2 renewal type for this subsystem. The renewal cost is 55 % of the replacement cost (Figure 6.5), and the operational cost is also adjusted as follows:

- The operational cost now (base year) is equal to 2 % of the replacement cost (base value).
- The operational cost in $year_i$ can be increased from the base value if the performance in year i is less than that during the base year. In this case, operational cost = ($OSPI_i$ / $OSPI_{now}$) x (base value). The operational costs thus increase as the subsystem deteriorates.

For example, the total costs for water treatment (first subsystem) in year 1 are calculated as follows:

Renewal cost = 0.55 x $1,470,000 = $808,500 (renewal type 2)

Operational cost = base value only because $OSPI_1$ (1,797) is less than $OSPI_{now}$ (3850) = 2 % of $1,470,000 = $29,400

Total cost in year 1 = $808,500 + $29,400 = $837,900

As well, since all subsequent years will have an OSPI less than the base (3850), the total costs for water treatment in year 2: the operational costs remain as the base value of $29,000, as shown in Figure 6.6.

This Year:	2013				
Interest / Year:	0.04				
Budget (million/Year):	$5.00	$5.00	$5.00	$5.00	$5.00
Present worth / Year (million):	$4.91	$4.95	$4.98	$4.97	$4.46

No.	Desc.	Replacement Cost	Operational cost now	Decisions:		Renewal Cost	1	2	3	4	5
				Renewal year	Renewal Type		Cost in Year1	Cost in Year2	Cost in Year3	Cost in Year4	Cost in Year5
1	Water Treatment - Support	$1,470,000	$29,400	1	2	$808,500	$837,900	$29,400	$29,400	$29,400	$29,400
2	Chiller Unit(s) - Support	$4,508,000	$90,160	1	2	$2,479,400	$2,569,560	$90,160	$90,160	$90,160	$90,160
3	Boiler Unit(s) - Support	$2,847,600	$56,952	5	3	$1,993,320	$62,548	$68,144	$73,740	$79,336	$2,050,272

Calculated based on the costs from RS Means (2008)

Renewal type 2 is 55% (Figure 6.5) of the replacement cost

(Total cost)$_1$ = 808,500 + 29,400

Figure 6.6: Annual renewal and operational costs

Based on the renewal decision and the cost calculations for all of the subsystems, the annual costs are summed, and the present value of the allocated fund for each year is calculated using an interest rate (ir) of 4 %, as follows:

$$\text{Allocated fund}_i = \sum_{subsystem\, n=1}^{N} Cost_{ni} / (1+ir)^i \qquad \textbf{6.3}$$

where i is the year number, n is the subsystem number, and ir is the applicable interest rate per year (user input).

These calculations are shown at the top of Figure 6.6, along with the budget for capital renewal for each year.

6.2.5 Fund-allocation optimization

To optimize the renewal decisions (renewal year and renewal type) for each subsystem, with consideration of the budget constraints, the developed model uses a genetic algorithm (GA) technique, which has a capability to handle large scale problems, to assess different combinations of decisions until a near-optimum solution is obtained. For testing and validation, the developed model was applied to the 44 top-priority subsystems identified in the hospital 1 case study. To arrive at the best decision, a number of experiments were conducted using two different objective functions:

- **Objective function 1**: Minimize the average priority index (OSPI) for all of the subsystems (i.e., maximize the overall performance of all of the related subsystems).
- **Objective function 2**: Maximize the number of subsystems that exhibit improvement in a single condition KPI or in all of them.

The first objective function "Objective function 1", as shown in Figure 6.7 is to minimize the average priority for all subsystem s has been defined as follows:

Minimum average priority = $\sum_{1}^{n}\sum_{1}^{m} OSPI_m / n.m$

Where,

OSPI = overall subsystem priority index

m = number of subsystems, and n = number of years

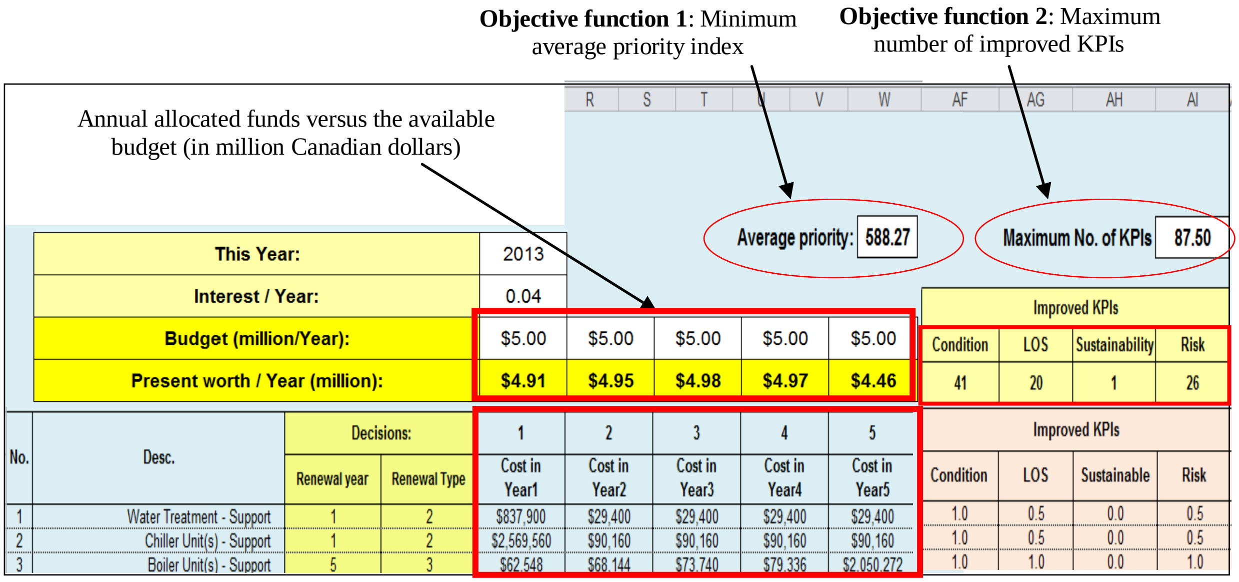


Figure 6.7: Objective functions and annual fund allocation

Maximum number of improved KPIs "Objective function 2" is the sum of the improved KPIs, as shown in the Figure 6.7. After the optimization is run for a number of iterations, a near-optimum solution is determined.

6.3 Testing and Validation

For testing and validation purposes, the developed capital-renewal optimization model was applied for the evaluation of the 44 top-priority subsystems of case study 1 (hospital 1). To optimize decisions, a number of experiments were conducted using two alternative objective functions: minimizing the average priority index of all subsystems, and maximizing the sum of the improved KPIs in all subsystems, as shown in Table 6.2. In all experiments, for the renewal of these subsystems, an annual renewal budget limit of $5 million was used, which corresponds to the hospital's actual budget limit, as shown in Table 4.2. It should be noted that all monetary amounts mentioned in this chapter represent Canadian dollars.

Table 6.2: Six scenarios for testing and validation (30 min runtime optimization)

	Scenario	1	*2	3	4	5	6
Given	**Objective function**	(1) Minimum renewal priority			(2) Maximum KPI improvement		
	Available budget	**$4.00**	**$5.00**	**$ 6.00**	**$ 4.00**	**$ 5.00**	**$ 6.00**
Results	**Average priority** (smaller is preferable):	**630.62**	**588.27**	**476.60**	**795.42**	**606.97**	**599.72**
	Condition KPI (larger is preferable)	38	41	43	33	40	41
	LOS KPI (larger is preferable)	17	20	23	27	28	33
	Sustainability KPI (larger is preferable)	2	1	3	19	17	23
	Risk KPI (larger is preferable)	22	26	28	29	33	37
	Number of improved KPIs (larger is preferable):	**79.00**	**87.50**	**97.00**	**108.00**	**117.5**	**133.50**
	Annual total allocated money						
	Year 1	$4.00	$4.91	$5.95	$3.99	$5.00	$5.99
	Year 2	$3.96	$4.95	$5.99	$3.93	$4.98	$5.97
	Year 3	$3.92	$4.98	$5.95	$3.93	$4.99	$5.99
	Year 4	$3.93	$4.97	$5.83	$3.99	$4.96	$5.98
	Year 5	$3.82	$4.46	$4.37	$3.99	$4.97	$5.87
	Total life cycle cost (TLCC)	**$19.63**	**$24.27**	**$28.09**	**$19.83**	**$24.89**	**$29.80**
	Number of subsystems renewed (larger is preferable)	**38**	**41**	**43**	**38**	**40**	**39**
	Number of subsystems not renewed	**6**	**3**	**1**	**6**	**4**	**5**
	Year 1	8	5	11	5	6	7
	Year 2	16	24	20	6	14	13
	Year 3	10	8	7	10	10	9
	Year 4	3	3	3	8	5	6
	Year 5	1	3	2	9	5	4
	Renewal types						
	Type 1	10	11	10	5	9	7
	Type 2	22	24	20	4	6	3
	Type 3	8	9	10	7	9	9
	Type 4	2	1	3	20	18	25

Note: (*) Base scenario; $ = Canadian dollars in millions; values are for 44 subsystems; interest rate (ir) = 4 %

As listed in Table 6.2, six scenarios with different budget levels and objective functions were implemented using the model developed. The results of these experiments showed that the model performed consistently. The base scenario is scenario 2, in which objective function 1 (minimum average priority index) was used with a $5 million budget. To implement the GA optimization, a commercial GA tool called Evolver, which functions as an add-on to Excel, has been utilized because of its ease-of use and known flexibility. Figure 6.8 illustrates the application of Evolver to the spreadsheet model for the scenario 2 experiment.

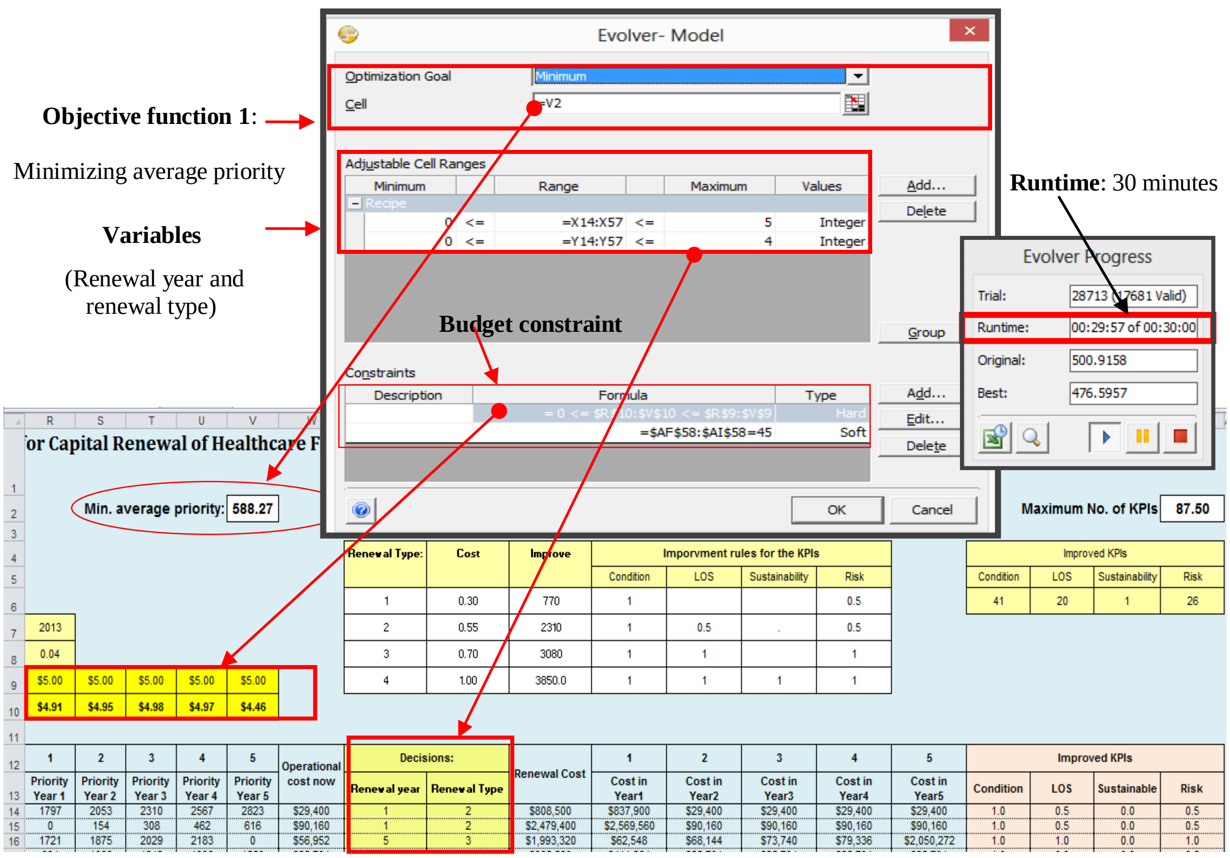


Figure 6.8: Main features of Evolver

Partial results of running this scenario are shown in Figure 6.2: the first two subsystems (water treatment and the chillers), which have been assigned a high priority, were selected for renewal in the first year with a renewal type of 2. The minimum average priority index obtained from the optimization is 588.27, the circled item at the top left of the spreadsheet.

The six scenarios listed in Table 6.2 provide a comparison of the results of the two objective functions for annual renewal budgets of $4 million, $5 million, and $6 million, respectively. The runtime of the optimization process, for all scenarios, was only 30 minutes. In general, the optimization results for all scenarios are consistent and logical. For example, increasing the budget level from $4 million to $6 million resulted in both improved average priority values and an increased number of improved KPIs. In fact, for all scenarios, increasing the budget resulted in improvement with respect to a greater number of KPIs (condition, LOS, sustainability, risk). It should also be noted that a significant number of the subsystems have been assigned for renewal in the first three years, as shown in Figure 6.9 and Figure 6.10. In terms of renewal type, increasing the budget limit from $4 million to $6 million caused the model to assign type 4 more frequently as the renewal type (full replacement), as shown at the bottom of Table 6.2.

Objective function 1: minimum average priority

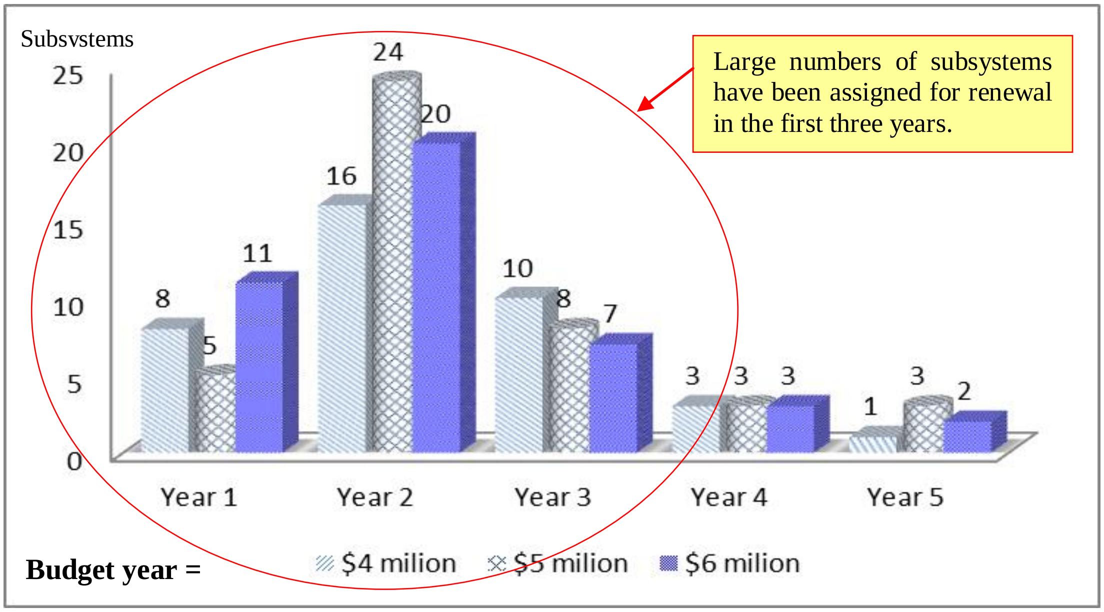


Figure 6.9: Objective function 1: numbers of renewed subsystems

Objective function 2: maximum number of KPIs improved

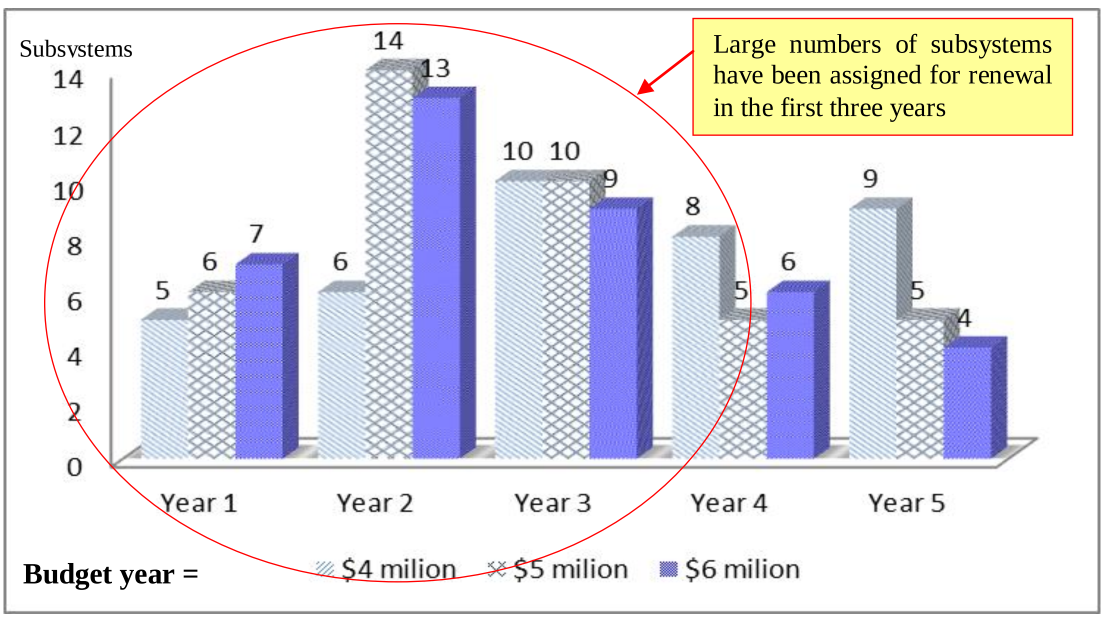


Figure 6.10: Objective function 2: numbers of renewed subsystems

With respect to processing time, the Evolver software was used for the scenario 2 experiment, with a variety of processing times. The results are reported in Table 6.3.

Table 6.3: GA processing time for the scenario 2 experiment

Scenario 2 (Table 6.2)	**4 min**	**15 min**	**30 min**	**2 h**
Average priority (smaller is preferable)	648.42	549.15	522.16	518.87
Number of improved KPIs (larger is preferable)	94.5	92	89.5	88

As shown, the outcome of the optimization improves significantly with longer processing times, up to about 30 minutes, after which the improvement is negligible. The processing time was therefore fixed at 30 minutes for all experiments.

As shown in Table 6.2, for scenario 2, the optimum decision was to fund the majority of subsystems with renewal type 1 (for 11 subsystems) and renewal type 2 (for 24 subsystems) (i.e., least expensive) being the option most often selected. These results represent a good allocation of funds under a strict budget.

6.4 Additional fund allocation experiments

The flexibility of the developed model was demonstrated through its use in two additional modes for allocating the subsystem renewal budget: simple ranking and partial optimization.

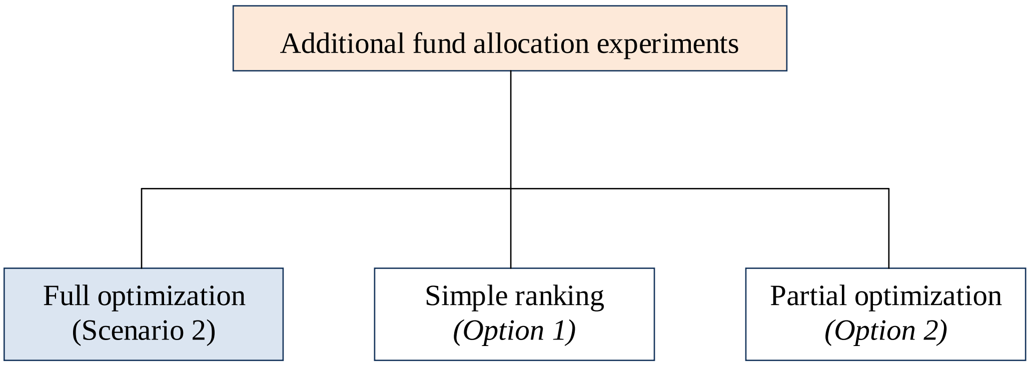
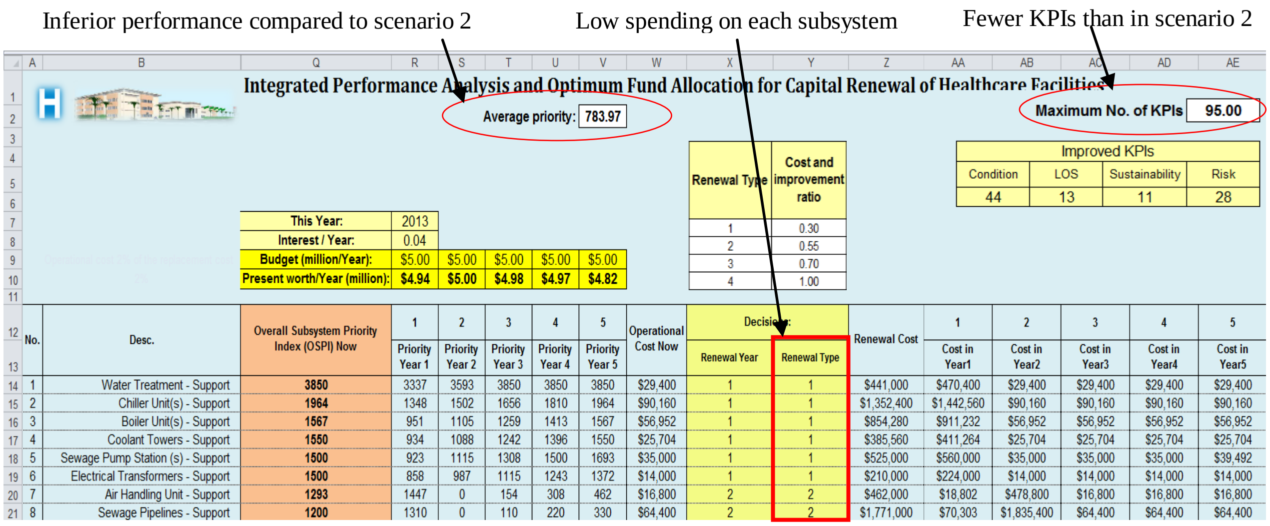


Figure 6.11: Additional experimental options for fund allocation

Simple ranking (option 1): In this option, for each subsystem, the user can manually select the renewal year and renewal type, in columns X and Y, with first consideration being given to the top-priority subsystems. The annual renewal costs are automatically calculated accordingly, as shown in Figure 6.12. The two cases illustrated in Figure 6.12 reveal the inefficiency of manual attempts, which cannot provide optimized decisions. The results produced for the base scenario listed in Table 6.2 is far superior to those shown in Figure 6.12.

a) Low spending on each subsystem



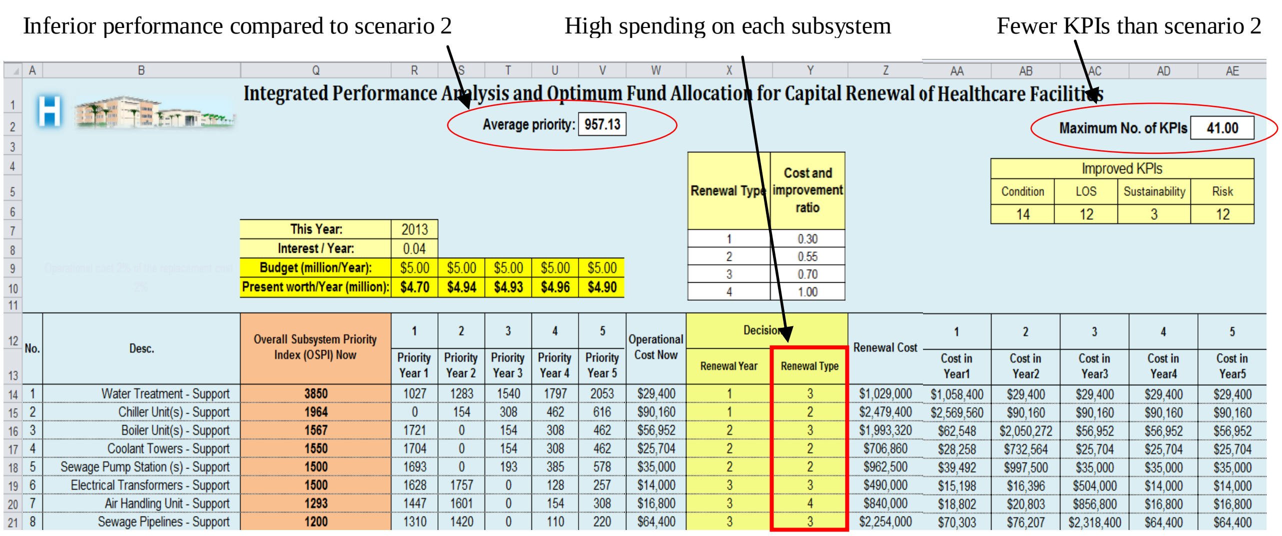
Improved KPIs			
Condition	LOS	Sustainability	Risk
44	13	11	28

Renewal Type	Cost and improvement ratio
1	0.30
2	0.55
3	0.70
4	1.00

This Year:	2013				
Interest / Year:	0.04				
Budget (million/Year):	$5.00	$5.00	$5.00	$5.00	$5.00
Present worth/Year (million):	$4.94	$5.00	$4.98	$4.97	$4.82

No.	Desc.	Overall Subsystem Priority Index (OSPI) Now	1 Priority Year 1	2 Priority Year 2	3 Priority Year 3	4 Priority Year 4	5 Priority Year 5	Operational Cost Now	Decisions: Renewal Year	Decisions: Renewal Type	Renewal Cost	1 Cost in Year1	2 Cost in Year2	3 Cost in Year3	4 Cost in Year4	5 Cost in Year5
1	Water Treatment - Support	3850	3337	3593	3850	3850	3850	$29,400	1	1	$441,000	$470,400	$29,400	$29,400	$29,400	$29,400
2	Chiller Unit(s) - Support	1964	1348	1502	1656	1810	1964	$90,160	1	1	$1,352,400	$1,442,560	$90,160	$90,160	$90,160	$90,160
3	Boiler Unit(s) - Support	1567	951	1105	1259	1413	1567	$56,952	1	1	$854,280	$911,232	$56,952	$56,952	$56,952	$56,952
4	Coolant Towers - Support	1550	934	1088	1242	1396	1550	$25,704	1	1	$385,560	$411,264	$25,704	$25,704	$25,704	$25,704
5	Sewage Pump Station (s) - Support	1500	923	1115	1308	1500	1693	$35,000	1	1	$525,000	$560,000	$35,000	$35,000	$35,000	$39,492
6	Electrical Transformers - Support	1500	858	987	1115	1243	1372	$14,000	1	1	$210,000	$224,000	$14,000	$14,000	$14,000	$14,000
7	Air Handling Unit - Support	1293	1447	0	154	308	462	$16,800	2	2	$462,000	$18,802	$478,800	$16,800	$16,800	$16,800
8	Sewage Pipelines - Support	1200	1310	0	110	220	330	$64,400	2	2	$1,771,000	$70,303	$1,835,400	$64,400	$64,400	$64,400

b) High spending on each subsystem



Improved KPIs			
Condition	LOS	Sustainability	Risk
14	12	3	12

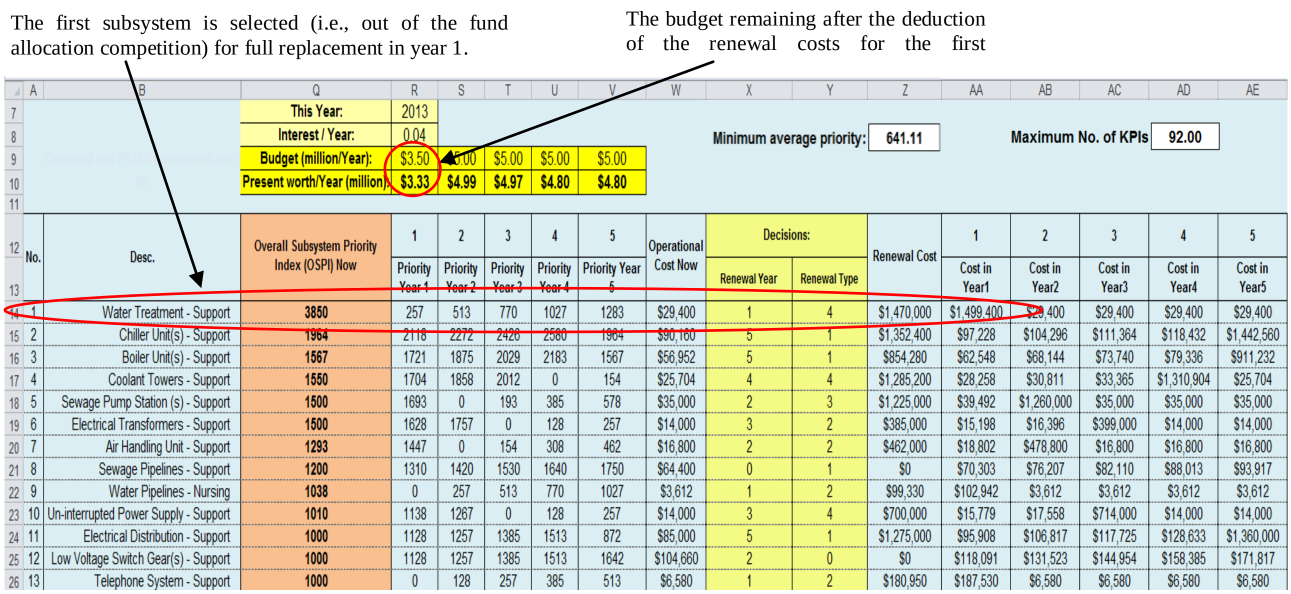
Renewal Type	Cost and improvement ratio
1	0.30
2	0.55
3	0.70
4	1.00

This Year:	2013				
Interest / Year:	0.04				
Budget (million/Year):	$5.00	$5.00	$5.00	$5.00	$5.00
Present worth/Year (million):	$4.70	$4.94	$4.93	$4.96	$4.90

No.	Desc.	Overall Subsystem Priority Index (OSPI) Now	1 Priority Year 1	2 Priority Year 2	3 Priority Year 3	4 Priority Year 4	5 Priority Year 5	Operational Cost Now	Decision: Renewal Year	Decision: Renewal Type	Renewal Cost	1 Cost in Year1	2 Cost in Year2	3 Cost in Year3	4 Cost in Year4	5 Cost in Year5
1	Water Treatment - Support	3850	1027	1283	1540	1797	2053	$29,400	1	3	$1,029,000	$1,058,400	$29,400	$29,400	$29,400	$29,400
2	Chiller Unit(s) - Support	1964	0	154	308	462	616	$90,160	1	2	$2,479,400	$2,569,560	$90,160	$90,160	$90,160	$90,160
3	Boiler Unit(s) - Support	1567	1721	0	154	308	462	$56,952	2	3	$1,993,320	$62,548	$2,050,272	$56,952	$56,952	$56,952
4	Coolant Towers - Support	1550	1704	0	154	308	462	$25,704	2	2	$706,860	$28,258	$732,564	$25,704	$25,704	$25,704
5	Sewage Pump Station (s) - Support	1500	1693	0	193	385	578	$35,000	2	2	$962,500	$39,492	$997,500	$35,000	$35,000	$35,000
6	Electrical Transformers - Support	1500	1628	1757	0	128	257	$14,000	3	3	$490,000	$15,198	$16,396	$504,000	$14,000	$14,000
7	Air Handling Unit - Support	1293	1447	1601	0	154	308	$16,800	3	4	$840,000	$18,802	$20,803	$856,800	$16,800	$16,800
8	Sewage Pipelines - Support	1200	1310	1420	0	110	220	$64,400	3	3	$2,254,000	$70,303	$76,207	$2,318,400	$64,400	$64,400

Figure 6.12: Fund allocation using a simple ranking (low and high spending)

Partial optimization (option 2): This option is a hybrid of simple ranking and optimization and can be useful for excluding some subsystems previously identified by the decision makers. The remaining budget is therefore left to be allocated based on the optimization process for the rest of the subsystems. For example, because of its importance, full replacement in the first year ($1,470,000) had been predetermined for the first high-priority subsystem. The remainder of the subsystems were thus left to compete for the remaining budget ($3,530,000). The results produced by this hybrid process are shown in Figure 6.13.



This Year:	2013				
Interest / Year:	0.04				
Budget (million/Year):	$3.50	$5.00	$5.00	$5.00	$5.00
Present worth/Year (million):	$3.33	$4.99	$4.97	$4.80	$4.80

Minimum average priority: 641.11 | Maximum No. of KPIs: 92.00

No.	Desc.	Overall Subsystem Priority Index (OSPI) Now	1 Priority Year 1	2 Priority Year 2	3 Priority Year 3	4 Priority Year 4	5 Priority Year 5	Operational Cost Now	Decisions: Renewal Year	Decisions: Renewal Type	Renewal Cost	1 Cost in Year1	2 Cost in Year2	3 Cost in Year3	4 Cost in Year4	5 Cost in Year5
1	Water Treatment - Support	3850	257	513	770	1027	1283	$29,400	1	4	$1,470,000	$1,499,400	$29,400	$29,400	$29,400	$29,400
2	Chiller Unit(s) - Support	1964	2118	2272	2426	2580	1964	$90,160	5	1	$1,352,400	$97,228	$104,296	$111,364	$118,432	$1,442,560
3	Boiler Unit(s) - Support	1567	1721	1875	2029	2183	1567	$56,952	5	1	$854,280	$62,548	$68,144	$73,740	$79,336	$911,232
4	Coolant Towers - Support	1550	1704	1858	2012	0	154	$25,704	4	4	$1,285,200	$28,258	$30,811	$33,365	$1,310,904	$25,704
5	Sewage Pump Station (s) - Support	1500	1693	0	193	385	578	$35,000	2	3	$1,225,000	$39,492	$1,260,000	$35,000	$35,000	$35,000
6	Electrical Transformers - Support	1500	1628	1757	0	128	257	$14,000	3	2	$385,000	$15,198	$16,396	$399,000	$14,000	$14,000
7	Air Handling Unit - Support	1293	1447	0	154	308	462	$16,800	2	2	$462,000	$18,802	$478,800	$16,800	$16,800	$16,800
8	Sewage Pipelines - Support	1200	1310	1420	1530	1640	1750	$64,400	0	1	$0	$70,303	$76,207	$82,110	$88,013	$93,917
9	Water Pipelines - Nursing	1038	0	257	513	770	1027	$3,612	1	2	$99,330	$102,942	$3,612	$3,612	$3,612	$3,612
10	Un-interrupted Power Supply - Support	1010	1138	1267	0	128	257	$14,000	3	4	$700,000	$15,779	$17,558	$714,000	$14,000	$14,000
11	Electrical Distribution - Support	1000	1128	1257	1385	1513	872	$85,000	5	1	$1,275,000	$95,908	$106,817	$117,725	$128,633	$1,360,000
12	Low Voltage Switch Gear(s) - Support	1000	1128	1257	1385	1513	1642	$104,660	2	0	$0	$118,091	$131,523	$144,954	$158,385	$171,817
13	Telephone System - Support	1000	0	128	257	385	513	$6,580	1	2	$180,950	$187,530	$6,580	$6,580	$6,580	$6,580

Figure 6.13: Partial optimization option

6.5 Conclusions

This chapter has introduced the main features of the developed capital-renewal optimization model: performance assessment, deterioration, renewal types and performance improvement, LCCA, and optimization for fund allocation. To validate the usefulness and practicality of the model, it was applied for case study 1 (hospital 1). The results have been presented for six different scenarios with varying annual budgets. A processing time of 30 minutes was determined to be reasonable. The model defines an appropriate year for renewal, identifies renewal types that minimize the average priority index for the whole network of subsystems, and maximizes the number of KPIs improved. The results produced by the model are far superior to those obtained with simple ranking approaches. The model can also operate either in full optimization mode or as a hybrid of manual and optimization modes.

Chapter 7

Conclusions and Future Research

7.1 Summary and Conclusions

Healthcare facilities are among the most challenging assets to maintain and modernize. Because many healthcare facilities are aging and involve specialized equipment and functional spaces, management's decisions of prioritizing capital renewals have become an enormous challenge, particularly under limited budgets. Such decisions require accurate performance assessment of all the facility subsystems, in addition to a structured approach to prioritize the competing subsystems and optimize fund allocation.

The literature shows that condition KPI has been used as the primary indicator of facility performance, overlooking other important criteria that have recently come into use, including: level of service (LOS), sustainability, and risk of failure. Most of the available decision support systems for facility management also deal with day-to-day maintenance activities, and only a small number offer limited support for renewal planning. As well, many fundamental asset management functions, such as performance assessment modeling and renewal prioritization, are not supported by the majority of these systems.

This research has therefore introduced a practical and comprehensive framework that renders the capital renewal process more structured, less time-consuming, and more appropriate for the specialized needs of healthcare facilities, particularly hospitals. The developed framework integrates five main functions: (1) a two-dimensional hierarchy of hospital systems and spaces; (2) a multi-criteria performance assessment process; (3) a visual all-on-site inspection process; (4) a prioritization mechanism; and (5) a capital-renewal optimization process. The first four functions of the proposed framework identify the overall subsystem importance (OSI), the overall subsystem deficiency (OSD), the overall priority index (OSPI), and the overall facility (building) performance index (OBPI).

A two-part questionnaire survey was used in order to gather the data necessary for the development and validation of the proposed framework. Part I obtained the relative importance of the main functional zones and spaces, systems, and subsystems, along with the applicable KPIs that best measure the performance of each subsystem and the relative importance of each KPI. The survey was completed by experts at four general hospitals in both Canada and Libya. Based on the data collected, some of the general findings are as follows: (1) the support zone is the most important zone (60 %), followed by the clinical and nursing zones (20 % each); (2) the subsystems that entail the greatest risk are the electrical, HVAC, medical gases, and fire subsystems; (3) the percentages of subsystems that should be evaluated in terms of the condition, LOS, sustainability, and risk are 100 %, 92 %, 17 %, and 91 %, respectively; and (4) the relative importance levels of the quality of indoor spaces with respect to air, water, light, and noise are 29 %, 29 %, 21 %, and 21 %, respectively. Part II of the survey was then employed for the gathering of data from the maintenance departments with respect to the capital renewal practices in effect at the case study hospitals.

To validate the performance assessment and prioritization functions of the developed framework, a field assessment was conducted at two case study hospitals. First, the visual inspection application was configured for assessment of the subsystems and spaces in the case study hospitals. Based on the field assessment, the overall performance of hospital 1 was found to be good (90 %) and the subsystems designated for renewal included water treatment, chillers, boilers, the sewage pump station, electrical distribution, and transformers. A high degree of correlation was found between the prioritization list produced by the framework and the list prepared by the hospita1 maintenance department. For the second hospital, the overall performance was found to be very low (52 %) due to the poor performance of its architectural, electrical, communication, and mechanical systems, as evidenced by the major rehabilitation required in important subsystems such as medical gases, doors, windows, floors, water pipelines, sewage pipelines, and fixtures. These two case studies demonstrated the functionality of the proposed framework, highlighted the reduced effort required to produce the results, and underlined the benefits provided, which were very much appreciated by the hospital maintenance experts.

The proposed multi-criteria facility assessment mechanism and prioritization function were then used in order to develop a capital-renewal optimization model that integrates deterioration modeling, renewal types, performance improvement models, and life cycle cost analysis (LCCA). The results of the application of the model for the first case study (hospital 1) were analyzed with respect to six scenarios that involved differing budget constraints and objective functions. The renewal timing and renewal types selected by the framework for all of the subsystems improved the overall performance of the facility with respect to any desirable KPIs. The model can operate in either full optimization mode or as a hybrid of manual and optimization modes. The extensive experimentation demonstrated that the model produces results that are far superior to those obtained by simple ranking approaches. Overall, this framework re-engineers the traditional processes of performance assessment for the building infrastructure and greatly improves the decision-making process for capital renewal.

7.2 Research Contributions

Based on the development during the course of the research, the contributions of this work include the following:

- **Better understanding of the interactions among building systems and spaces:** This research introduced a two-dimensional hierarchy that integrates the physical systems and the various zones/spaces within a hospital building, along with indoor quality factors associated with the spaces. All of these elements have been linked through the LOS key performance indicator, which enhances the comprehensiveness and accuracy of the performance assessment process.
- **Improved understanding of performance assessment processes:** A spreadsheet-based questionnaire survey has been design as a user-friendly approach to data collection from hospitals experts related to the challenges they face in performance assessment and their opinion about the important parameters that are useful in designing the proposed framework. The questionnaire design reduced data entry time, maintained the interest of the interviewees, and obtained most complete and accurate data. Spreadsheet functions and macros were used in the survey spreadsheets so that the interviewee could easily select a variety of options from dropdown menus and thus quickly complete the survey.
- **Restructuring of the inspection and performance assessment process:** The research resulted in the improvement and restructuring of the current inspection and performance assessment process for healthcare facilities in general and for hospital buildings in particular. The performance assessment process was made more comprehensive and practical through the use of four key performance indicators to cover four dimensions: condition, LOS, sustainability, and risk. The research also led to the development of an all-on-site visual inspection application for portable devices that enables the entire inspection process for both the subsystems and spaces to be completed on-site. The application has a visual guidance

system that decreases the subjectivity involved in condition assessment and allows the user to digitally mark the location of critical items directly on floor plans.

- **Practical prioritization and optimization functions for capital renewal:** The new framework has two functions: one for prioritizing subsystems according to their overall priority index and a second for optimizing fund allocation. The latter is based on the formulation of the overall subsystem priority index (OSPI), which incorporates the current physical condition of the subsystem and the KPIs that best describe its performance. The fund allocation optimization also proved to be flexible and provides much better results than traditional simple ranking approaches.
- **Expandable prototype:** The research included the development of a flexible computerized prototype of the proposed framework that can be adapted for other building assets, such as schools, hotels, offices, and commercial buildings. This feature significantly multiplies the value of the research because these assets represent a large portion of the civil infrastructure.

7.3 Future research

Several potential improvements can be incorporated into the framework developed for this thesis, and a number of additional related areas of research can also be explored:

- Expand the KPIs to include additional detail. For example, the LOS for a space could include features such as the size of the space, furniture layout, etc. Similarly, the sustainability and risk KPIs could be expanded to include numerous sub-items.

  Collect historical data related to renewal contracts in order to identify optional renewal strategies, costs, and potential for performance improvement.

- Thoroughly examine the difference between the deterioration rate in the condition KPI of a subsystem versus other KPIs: LOS, sustainability, and risk.
- Develop enhanced performance deterioration models for the different subsystems.
- Expand the visual guidance database to include additional images of a variety of subsystems.
- Incorporate a comprehensive reporting system.
- Integrate the organization's bank and project delivery mechanism so that the subsystem's performance can be updated based on renewal contracts that have been executed.
- Expand the LCCA to include more than five years.
- Incorporate practical reporting features for tracking the history of subsystem performance.
- Improve the optimization to address larger-scale problems using techniques other than GAs.

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Appendix A

Case study 1 (Hospital 1): Prioritized subsystems using the developed framework

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	Subsystem	RI	System	RI	Zone	RI	Overall Subsystem Importance (OSI)	Visual assessment (Condition index)	Condition		LOS		Sustainability		Risk		Overall Subsystem Deficiency (OSD)	Minimum Acceptable Condition	Eligibility for renewal	Priority Index (OSPI = OSI x OSD)
3	Water Treatment - Support	125	Mech.	80	Support	60	60	38	0.25	62.5	0.25	69	0.25	63	0.25	63	64	90	Yes	3,850
4	Chiller Unit(s) - Support	125	Mech.	80	Support	60	60	63	0.36	37.5	0.36	38	0.00	38	0.27	19	33	90	Yes	1,964
5	Boiler Unit(s) - Support	75	Mech.	80	Support	60	36	50	0.36	50	0.36	51	0.00	50	0.27	25	44	90	Yes	1,567
6	Coolant Towers - Support	125	Mech.	80	Support	60	60	69	0.36	31.25	0.27	32	0.00	31	0.36	16	26	90	Yes	1,550
7	Sewage Pump Station (s) - Support	125	Mech.	80	Support	60	60	75	0.27	25	0.27	25	0.20	25	0.27	25	25	90	Yes	1,500
8	Electrical Transformers - Support	125	Elec. & Comm.	80	Support	60	60	75	0.33	25	0.33	25	0.00	25	0.33	25	25	90	Yes	1,500
9	Air Handling Unit - Support	125	Mech.	80	Support	60	60	75	0.40	25	0.30	26	0.00	25	0.30	13	22	90	Yes	1,293
10	Sewage Pipelines - Support	100	Mech.	80	Support	60	48	75	0.14	25	0.36	25	0.14	25	0.36	25	25	90	Yes	1,200
11	Water Pipelines - Nursing	100	Mech.	100	Nursing	20	20	50	0.28	50	0.28	57	0.15	50	0.28	50	52	100	Yes	1,038
12	Un-interrupted Power Supply - Support	125	Elec. & Comm.	80	Support	60	60	75	0.33	25	0.33	25	0.00	25	0.33	1	17	90	Yes	1,010
13	Electrical Distribution - Support	100	Elec. & Comm.	80	Support	60	48	75	0.33	25	0.33	25	0.00	25	0.33	13	21	90	Yes	1,000
14	Low Voltage Switch Gear(s) - Support	100	Elec. & Comm.	80	Support	60	48	75	0.33	25	0.33	25	0.00	25	0.33	13	21	90	Yes	1,000
15	Telephone System - Support	100	Elec. & Comm.	80	Support	60	48	75	0.33	25	0.33	25	0.00	25	0.33	13	21	90	Yes	1,000
16	Closed-Circuit Television (CCTV) - Support	100	Elec. & Comm.	80	Support	60	48	75	0.22	25	0.22	25	0.00	25	0.56	10	17	90	Yes	800
17	Sewage Fixtures - Support	60	Mech.	80	Support	60	29	75	0.14	25	0.36	25	0.14	25	0.36	25	25	90	Yes	720
18	Water Fixtures - Support	60	Mech.	80	Support	60	29	75	0.30	25	0.30	32	0.09	25	0.30	13	23	90	Yes	669
19	Standby Generators - Support	125	Elec. & Comm.	80	Support	60	60	88	0.33	12.5	0.33	13	0.00	13	0.33	6	10	90	Yes	625
21	Water Pipelines - Clinical	100	Mech.	100	Clinical	20	20	75	0.28	25	0.28	32	0.15	25	0.28	25	27	100	Yes	538
22	Water Fixtures - Nursing	60	Mech.	100	Nursing	20	12	50	0.30	50	0.30	57	0.09	50	0.30	25	44	100	Yes	533
23	Ducts/Diffusers - Clinical	100	Mech.	100	Clinical	20	20	75	0.19	25	0.63	26	0.00	25	0.19	25	26	100	Yes	512
24	Ducts/Diffusers - Nursing	100	Mech.	100	Nursing	20	20	75	0.19	25	0.63	26	0.00	25	0.19	25	26	100	Yes	512
26	Sewage Pipelines - Clinical	100	Mech.	100	Clinical	20	20	75	0.14	25	0.36	25	0.14	25	0.36	25	25	100	Yes	500
27	Sewage Pipelines - Nursing	100	Mech.	100	Nursing	20	20	75	0.14	25	0.36	25	0.14	25	0.36	25	25	100	Yes	500
28	Signage - Clinical	100	Arch.	90	Clinical	20	18	75	0.50	25	0.50	25	0.00	25	0.00	0	25	90	Yes	450
30	Electrical Distribution - Clinical	100	Elec. & Comm.	100	Clinical	20	20	75	0.33	25	0.33	25	0.00	25	0.33	13	21	100	Yes	417
31	Electrical Distribution - Nursing	100	Elec. & Comm.	100	Nursing	20	20	75	0.33	25	0.33	25	0.00	25	0.33	13	21	100	Yes	417
32	Low Voltage Switch Gear(s) - Clinical	100	Elec. & Comm.	100	Clinical	20	20	75	0.33	25	0.33	25	0.00	25	0.33	13	21	100	Yes	417
33	Low Voltage Switch Gear(s) - Nursing	100	Elec. & Comm.	100	Nursing	20	20	75	0.33	25	0.33	25	0.00	25	0.33	13	21	100	Yes	417
34	Telephone System - Clinical	100	Elec. & Comm.	100	Clinical	20	20	75	0.33	25	0.33	25	0.00	25	0.33	13	21	100	Yes	417
35	Telephone System - Nursing	100	Elec. & Comm.	100	Nursing	20	20	75	0.33	25	0.33	25	0.00	25	0.33	13	21	100	Yes	417
36	Windows - Clinical	100	Arch.	90	Clinical	20	18	75	0.25	25	0.25	25	0.25	25	0.25	10	21	90	Yes	383
38	Closed-Circuit Television (CCTV) - Clinical	100	Elec. & Comm.	100	Clinical	20	20	75	0.22	25	0.22	25	0.00	25	0.56	10	17	100	Yes	333
39	Closed-Circuit Television (CCTV) - Nursing	100	Elec. & Comm.	100	Nursing	20	20	75	0.22	25	0.22	25	0.00	25	0.56	10	17	100	Yes	333
40	Sewage Fixtures - Clinical	60	Mech.	100	Clinical	20	12	75	0.14	25	0.36	25	0.14	25	0.36	25	25	100	Yes	300
41	Sewage Fixtures - Nursing	60	Mech.	100	Nursing	20	12	75	0.14	25	0.36	25	0.14	25	0.36	25	25	100	Yes	300
42	Water Fixtures - Clinical	60	Mech.	100	Clinical	20	12	75	0.30	25	0.30	32	0.09	25	0.30	13	23	100	Yes	279
43	Nurse Call System - Clinical	60	Elec. & Comm.	100	Clinical	20	12	75	0.33	25	0.33	25	0.00	25	0.33	18	23	100	Yes	270
44	Nurse Call System - Nursing	60	Elec. & Comm.	100	Nursing	20	12	75	0.33	25	0.33	25	0.00	25	0.33	18	23	100	Yes	270
46	Master Clock System - Clinical	60	Elec. & Comm.	100	Clinical	20	12	75	0.33	25	0.33	25	0.00	25	0.33	13	21	100	Yes	250
47	Master Clock System - Nursing	60	Elec. & Comm.	100	Nursing	20	12	75	0.33	25	0.33	25	0.00	25	0.33	13	21	100	Yes	250
48	Elevators Power Supply Cables - Clinical	100	Mech.	100	Clinical	20	20	90	0.30	10	0.40	10	0.00	10	0.30	10	10	100	Yes	200
49	Elevators Power Supply Cables - Nursing	100	Mech.	100	Nursing	20	20	90	0.30	10	0.40	10	0.00	10	0.30	10	10	100	Yes	200
50	Elevators Mechanical Room - Clinical	100	Mech.	100	Clinical	20	20	90	0.30	10	0.40	10	0.00	10	0.30	4	8	100	Yes	164
51	Elevators Mechanical Room - Nursing	100	Mech.	100	Nursing	20	20	90	0.30	10	0.40	10	0.00	10	0.30	4	8	100	Yes	164

Appendix B

Case study 2 (Hospital 2): Prioritized subsystems using the developed framework

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	Subsystem	RI	System	RI	Zone	RI	Overall Subsystem Importance (OSI)	Visual Assessment (Condition Index)	Condition		LOS		Sustainability		Risk		Overall Subsystem Deficiency (OSD)	Minimum Acceptable Condition	Eligibility for Renewal	Priority Index (OSPI = OSI x OSD)
2									Wt.	Deficiency	Wt.	Deficiency	Wt.	Deficiency	Wt.	Deficiency				
3	Medical Gases Source Equipment - Support	125	Mech.	80	Support	60	60	50	0.33	50	0.33	50	0.00	50	0.33	25	42	90	Yes	2,500
4	Medical Gases Valves - Support	100	Mech.	80	Support	60	48	50	0.33	50	0.33	50	0.00	50	0.33	50	50	90	Yes	2,400
5	Water Fixtures - Support	100	Mech.	80	Support	60	48	50	0.38	50	0.38	50	0.12	50	0.12	25	47	90	Yes	2,262
6	Water Pipelines - Support	100	Mech.	80	Support	60	48	50	0.32	50	0.32	50	0.18	50	0.18	25	46	90	Yes	2,187
7	Medical Gases Compressor - Support	125	Mech.	80	Support	60	60	50	0.33	50	0.33	50	0.00	50	0.33	5	35	90	Yes	2,100
8	Medical Gases Pipelines - Support	100	Mech.	80	Support	60	48	50	0.33	50	0.33	50	0.00	50	0.33	25	42	90	Yes	2,000
9	Sewage Pipelines - Support	100	Mech.	80	Support	60	48	75	0.18	25	0.45	25	0.18	25	0.18	25	25	90	Yes	1,200
10	Sewage Fixtures - Support	100	Mech.	80	Support	60	48	75	0.18	25	0.45	25	0.18	25	0.18	25	25	90	Yes	1,200
11	Nurse Call System - Support	100	Elec. & Comm.	80	Support	60	48	75	0.33	25	0.33	25	0.00	25	0.33	17.5	23	90	Yes	1,080
13	Water Pipelines - Nursing	100	Mech.	100	Nursing	20	20	50	0.32	50	0.32	50	0.18	50	0.18	50	50	100	Yes	1,000
14	Water Pipelines - Clinical	100	Mech.	100	Clinical	20	20	50	0.32	50	0.32	50	0.18	50	0.18	50	50	100	Yes	1,000
15	Sewage Pipelines - Nursing	100	Mech.	100	Nursing	20	20	50	0.18	50	0.45	50	0.18	50	0.18	50	50	100	Yes	1,000
16	Sewage Pipelines - Clinical	100	Mech.	100	Clinical	20	20	50	0.18	50	0.45	50	0.18	50	0.18	50	50	100	Yes	1,000
17	Sewage Fixtures - Nursing	100	Mech.	100	Nursing	20	20	50	0.18	50	0.45	50	0.18	50	0.18	50	50	100	Yes	1,000
18	Sewage Fixtures - Clinical	100	Mech.	100	Clinical	20	20	50	0.18	50	0.45	50	0.18	50	0.18	50	50	100	Yes	1,000
19	Low Voltage Switch Gear(s) - Support	100	Elec. & Comm.	80	Support	60	48	75	0.33	25	0.33	25	0.00	25	0.33	12.5	21	90	Yes	1,000
20	Electrical Distribution - Support	100	Elec. & Comm.	80	Support	60	48	75	0.33	25	0.33	25	0.00	25	0.33	12.5	21	90	Yes	1,000
21	Telephone System - Support	100	Elec. & Comm.	80	Support	60	48	75	0.27	25	0.36	25	0.00	25	0.36	12.5	20	90	Yes	982
22	Water Fixtures - Nursing	100	Mech.	100	Nursing	20	20	50	0.38	50	0.38	50	0.12	50	0.12	25	47	100	Yes	942
23	Water Fixtures - Clinical	100	Mech.	100	Clinical	20	20	50	0.38	50	0.38	50	0.12	50	0.12	25	47	100	Yes	942
24	Windows - Nursing	100	Arch.	90	Nursing	20	18	50	0.26	50	0.26	50	0.35	50	0.14	20	46	70	Yes	825
25	Windows - Clinical	100	Arch.	90	Clinical	20	18	50	0.26	50	0.26	50	0.35	50	0.14	20	46	90	Yes	825
26	Floors - Nursing	100	Arch.	90	Nursing	20	18	50	0.37	50	0.27	50	0.00	50	0.37	20	39	70	Yes	702
27	Floors - Clinical	100	Arch.	90	Clinical	20	18	50	0.37	50	0.27	50	0.00	50	0.37	20	39	90	Yes	702
28	Doors - Nursing	100	Arch.	90	Nursing	20	18	50	0.30	50	0.30	50	0.00	50	0.41	20	38	70	Yes	681
29	Doors - Clinical	100	Arch.	90	Clinical	20	18	50	0.30	50	0.30	50	0.00	50	0.41	20	38	90	Yes	681
31	Medical Gases Pipelines - Nursing	100	Mech.	100	Nursing	20	20	75	0.33	25	0.33	25	0.00	25	0.33	25	25	100	Yes	500
32	Medical Gases Pipelines - Clinical	100	Mech.	100	Clinical	20	20	75	0.33	25	0.33	25	0.00	25	0.33	25	25	100	Yes	500
34	Signage - Nursing	60	Arch.	90	Nursing	20	11	50	0.34	50	0.47	50	0.00	50	0.19	20	44	70	Yes	479
35	Signage - Clinical	60	Arch.	90	Clinical	20	11	50	0.34	50	0.47	50	0.00	50	0.19	20	44	90	Yes	479
38	Nurse Call System - Nursing	100	Elec. & Comm.	100	Nursing	20	20	75	0.33	25	0.33	25	0.00	25	0.33	17.5	23	100	Yes	450
39	Nurse Call System - Clinical	100	Elec. & Comm.	100	Clinical	20	20	75	0.33	25	0.33	25	0.00	25	0.33	17.5	23	100	Yes	450
40	Low Voltage Switch Gear(s) - Nursing	100	Elec. & Comm.	100	Nursing	20	20	75	0.33	25	0.33	25	0.00	25	0.33	12.5	21	100	Yes	417
41	Low Voltage Switch Gear(s) - Clinical	100	Elec. & Comm.	100	Clinical	20	20	75	0.33	25	0.33	25	0.00	25	0.33	12.5	21	100	Yes	417
42	Electrical Distribution - Nursing	100	Elec. & Comm.	100	Nursing	20	20	75	0.33	25	0.33	25	0.00	25	0.33	12.5	21	100	Yes	417
43	Electrical Distribution - Clinical	100	Elec. & Comm.	100	Clinical	20	20	75	0.33	25	0.33	25	0.00	25	0.33	12.5	21	100	Yes	417
44	Telephone System - Nursing	100	Elec. & Comm.	100	Nursing	20	20	75	0.27	25	0.36	25	0.00	25	0.36	12.5	20	100	Yes	409
45	Telephone System - Clinical	100	Elec. & Comm.	100	Clinical	20	20	75	0.27	25	0.36	25	0.00	25	0.36	12.5	20	100	Yes	409
47	Façade - Clinical	100	Arch.	90	Clinical	20	18	75	0.32	25	0.18	25	0.32	25	0.18	10	22	90	Yes	402
48	Medical Gases Valves - Nursing	100	Mech.	100	Nursing	20	20	75	0.33	25	0.33	25	0.00	25	0.33	10	20	100	Yes	400
49	Medical Gases Valves - Clinical	100	Mech.	100	Clinical	20	20	75	0.33	25	0.33	25	0.00	25	0.33	10	20	100	Yes	400
53	Ceilings - Clinical	60	Arch.	90	Clinical	20	11	75	0.28	25	0.28	25	0.15	25	0.28	10	21	90	Yes	224
56	Walls - Clinical	30	Arch.	90	Clinical	20	5	75	0.33	25	0.33	25	0.00	25	0.33	10	20	90	Yes	108