Space-Based Maintenance Management for Architectural Building Systems using Multi-Objective Optimization

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Abstract

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Public Buildings like universities and educational buildings are considered among the most challenging assets to maintain and modernize. Statistics show that the non-residential buildings are prone to a significant shortage in maintenance and rehabilitation expenditure. As per the Canadian infrastructures report card (2016), 42% of Municipal buildings rank between "fair" and "very poor". In addition, according to the American society of civil engineering (ASCE) (2017) the school sector grade, which is the largest sector of educational buildings is D+ (poor condition). Thus, a maintenance optimization methodology is essential for these building types to appropriately plan for the maintenance of systems that are competing for limited funding. Upon reviewing the literature, a gap was revealed in the area of building maintenance, repair and rehabilitation, which is the lack of consideration of the space type inside the building and how different space types affect the maintenance planning process. Considering the fact that any building is composed of different space types having variable needs, requirements and functions that help in supporting the overall function of the building facility, therefore, not including the space types and functions as part of the maintenance plan would result in a loss in the overall functionality. Hence, the main objective of this research is to develop a maintenance optimization model which takes the space type into account and accordingly optimize the maintenance actions to be implemented inside a building.

To achieve the main objective the following sub-objectives were identified: 1) review the maintenance prioritization and optimization methods for buildings maintenance, 2)

develop a deterioration models for building systems and 3) establish an optimization model for buildings maintenance. The methodology encompasses three main phases. First, a space-based condition assessment, is adopted as a part of this research to determine weights of the spaces and the different systems inside each space of the building. Second, a Weibull Distribution model, is utilized to predict the future condition of building systems inside each space by modeling their deterioration over the time. Finally, a Particle swarm optimization is employed to optimize the activity selection. A case study on educational buildings is leveraged to illustrate the applicability of the proposed model. Non-dominate solutions were established considering the defined constraints. The selected compromising solution result was 11.06 building condition with a total cost of $475,000. A Sensitivity analysis was conducted showing the impact of the systems service life on the space-based assessment and the maintenance cost. The output of this study is a framework that selects the best combinations of maintenance activities to be implemented inside a building, considering the varying space types and maintenance costs.

Acknowledgement

I would like to first thank GOD for granting me the health, peace, and wellness required to complete this course of study.

And, I would like to express my deepest appreciation to my parents and wife who are the main reason that I am standing at this point in my life.

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List of Nomenclatures and Abbreviations

BMMF: Building Maintenance Management Framework

M&R: Maintenance and Rehabilitation

CA: Condition Assessment

BCA: Building condition assessment

SBCA: Space-based Condition Assessment

BCI: Building Condition Index

BAH: Building Asset Hierarchy

BN: Bayesian Networks

MOO: Multi-Objective Optimization

GAs: Genetic Algorithm

ACO: Ant Colony Optimization

PSO: Particle Swarm Optimization

Multi-Objective Particle Swarm Optimization: (MOPSO)

BAR-Bones particle swarm optimization: BBPSO

BIM: Building Information Modeling

AHP: Analytic Hierarchical Process

SA**:** Sensitivity analysis

Chapter 1: Introduction

1.1 Overview

Building facility play a critical role in economic and social development as they are the foundations of any developed country's economy. The increase in the rehabilitation and maintenance costs plus the fact that most buildings are deteriorating increased the need for some cost-effective maintenance and rehabilitation strategies (Hudson et al. 1997).

Statistically in Canada and the United States, the non-residential buildings represent the largest part of infrastructure. This sector is then expected to experience the largest shortage in maintenance and rehabilitation expense (Statistics Canada 1995; US Census Bureau 1999; Elhakeem 2005).Statistics Canada reported that the average service life of the most educational building is 40 years. According to the same report in 2008 most of educational building's age is 20.1 years which shows that educational building had passed 51 % of their service life. In 2008, the gross stock of educational facilities amounted to $115.5 billion, nearly half of the nation's total institutional infrastructure. Infrastructures cost Canadian municipalities CAD$15 billion per year, of which 80% is spent on the repair and renewal of aging infrastructures (Ewada 2012).

As per the Canadian infrastructures report card (Canadian Infrastructure Report Card, 2016), 42% of Municipal buildings such as community and cultural centers libraries, police, fire and paramedic stations rank between "fair" and "very poor". in particular, and based on the same report, 28%, 12% and 5% are in a fair, poor and very poor conditions, respectively. The replacement costs for these buildings would run a total amount of approximately $32 billion.

In the United State, According to the ASCE infrastructure report card 2017, the overall grade of the school sector is grade D (poor condition) and more than half (53%) of public schools need repairs, renovations, and modernizations to be in "good" condition. The gap between the annual needed investment and the annual spending is $ 38 billion (ASCE 2017)

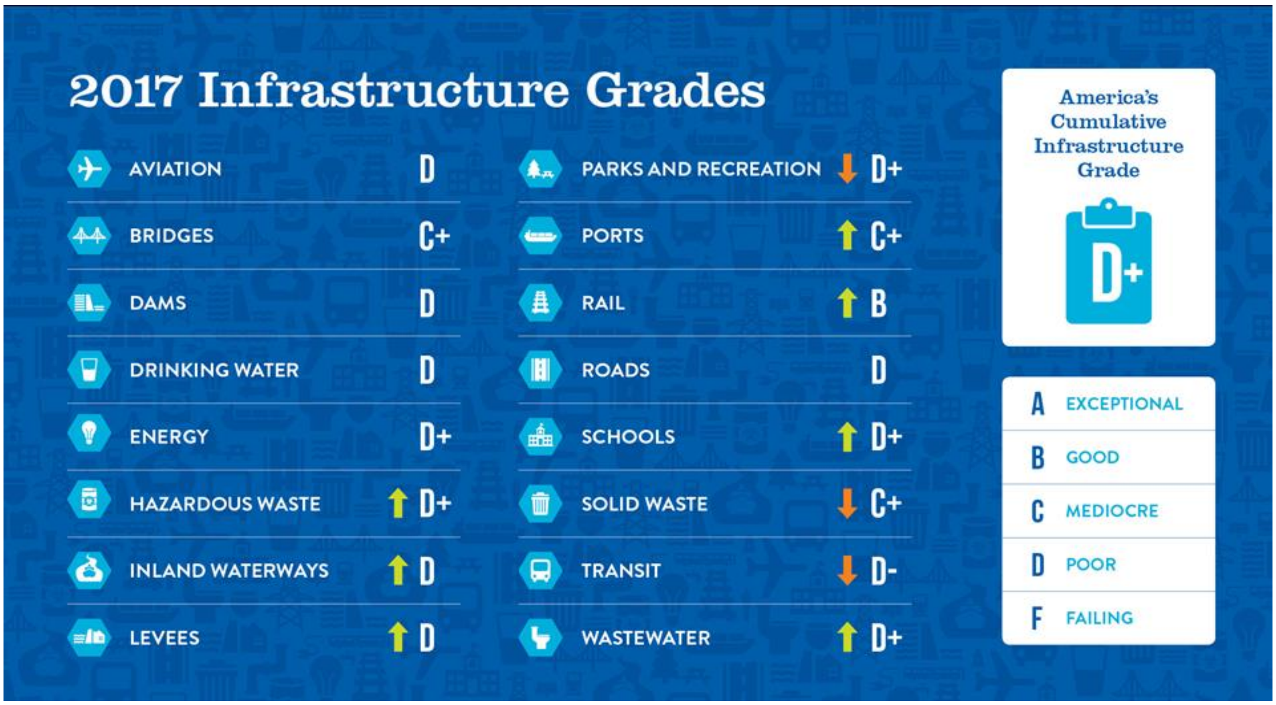


Figure 1-1 Report card for America's infrastructure (2017).

1.2 Problem Statement and Research Motivations

Public buildings are built to serve the need of the society and to play a major role in the development of communities (Bennett 2006). However, local environmental factor, use and abuse, levels of routine maintenance accomplished (Grussing 2015), initial design flaws and improper management cause these facilities to deteriorate (Fouial 2017).The increase of the deterioration rate is associated with increased demands to repair, as well as deficient budget allocation. Furthermore maintenance of facilities is complicated duo the fact that buildings consist of a unique vast number of components that have different needs. While there are common systems and component across all buildings, size, type, and configuration of these systems are usually distinct from one building to the other (Karanja 2017). This makes the task of maintaining the public facility even more challenging and difficult.

The type of the space and tasks held inside that space is the most important factor that should be considered in the maintenance optimization plan since the aim of any maintenance plan is to support the function of the space inside the building. For example, most of the educational process happens at the classrooms inside the educational buildings. Any defect that interrupts the learning processes should be maintained as soon as possible. A well-maintained classrooms have a positive impact on both students and teachers (Glen 2002). Another example, the function of the restrooms space type inside a building makes it important to maintain the mechanical systems compared to other categories such as architectural finishes under limited fund to ensure the functionality of space.

The maintenance optimization methods that were found in the literature either depend on the prioritizations of the maintenance tasks based on their importance or the optimization of these tasks based on a single objective. However, these models did not consider the space type inside the building, thus the development of an efficient space-based optimization framework for buildings is of great importance.

1.3 Research Objectives

The primary objective of this research is to study the area of maintenance prioritization and optimization of buildings, and to develop a practical and comprehensive framework to support and enhance efficient an optimum fund allocation for buildings.

Objectives are summarized as follows:

1) Review the maintenance prioritization and optimization methods for buildings.
2) Develop a deterioration model for building systems.
3) Develop an optimization model for maintenance management for buildings.

1.4 Dissertation Organization

The dissertation is organized as follows:

Chapter 1: Introduction: This chapter includes the introduction, the state of the Educational building's infrastructure in Canada, the problem statement and research motivations, research objectives, research methodology, and the dissertation organization.

Chapter 2: Literature Review: covers a comprehensive literature review required for the field of research. It is comprised of four main sections as follows: 1) condition assessment of buildings concept, 2) degradation models to predict deterioration buildings, 3) prioritization and optimization method for maintenance, and 4) an overview of evolutionary optimization algorithms.

Chapter 3: Methodology: This chapter covers the detailed research methodology for the maintenance optimization Framework through several steps, starting with condition assessment then the component deterioration and ending with particle swarm optimization.

Chapter 4: Case Study: demonstrates the model implementation. The relative importance weights of the spaces of the case study were defined. The case study continued with the condition prediction model. Systems deterioration curves were constructed, finally the implementation of the optimization model was described.

Chapter 5: result analysis: Presents a discussion on the condition assessment and condition prediction model results, then a Sensitivity analysis was conducted showing the impact of the systems service life on the condition assessment and the maintenance cost.

Chapter 6: Conclusions and limitation: It summarizes the overall findings of the thesis and presents the final conclusions. And it presents recommendations for future research in space-based building maintenance management.

Chapter 2: Literature Review

2.1 Overview

In this chapter, a maintenance prioritization and optimization methods for buildings are reviewed. The literature review starts with the maintenance and the definition various maintenance types. Some current prioritization methods and factor which affect the decision of setting priority in maintenance management will then be explained. These methods are important as they provide useful sight to develop an optimization model for Maintenance in buildings.

2.2 Building maintenance

Building management, in particular maintenance, refurbishment, and intervention features, is challenging for two major reasons. The first is that buildings present a high level of complexity as compared to other asset classes making them difficult to manage. Secondly, there are considerable limitations to specific and comprehensive asset management models for buildings as compared to other asset classes (Kalutara, 2013).

The maintenance phase represents 95% of any building lifecycle (Panchdhari, 2006).Maintenance and repair is a very important part of a building's lifecycle. A building maintenance practice is needed for every development because the building needs to be well maintained to retain the value of the property. If maintained properly, a building will continue fulfilling its function and will offer convenience to its occupants since maintenance ensures serviceability and safety. Although the construction of a new building requires huge investment and budget, the remaining lifecycle costs of operating, maintaining, and eventually, renovating a building can exceed initial costs (Morgado, 2017). Perret (1995) states that in a building whose service life is 50 years, the costs of the design and construction phase comprise approximately 20 to 25% of total cost, while the use and maintenance stages are responsible for roughly 75 to 85% of total cost. Furthermore, effective maintenance saves the building from the renewal option and creates a suitable environment that increases user productivity inside the space. Maintenance responsibility is considered one of the functions of the facility manager and includes preventive/corrective maintenance and capital asset renewal. Maintenance has been defined in a deferent way in the literature.table 2.1 illustraite some defenation of mainteance in the literature.

It can be concluded from most of the definitions that the main goal of any maintenance work is to make the building perform the functions for which it was designed. There are many types of building maintenance. According to the BS 3811 (1984), two main types are corrective maintenance and preventive maintenance.

As stated earlier, maintenance is important for the continuous performance of buildings. Unfortunately, there are numerous challenges to building maintenance management. Firstly, buildings, as any other asset, require a wide range of inspection, maintenance activities, repair, rehabilitation, and proper maintenance management to be restored to their original condition and to achieve great performance and efficacy out of the building component. Secondly, buildings consist of a unique and vast number of components that all have different needs. While there are common systems and components across all buildings, the size, type, and configuration of these systems is usually unique from one building to another (Karanja, 2017). For example, predicting the service life of building systems and components is a time-consuming and complex process and varies from component to component; the structural component, is expected to have a long service life, while others such as electrical components have a shorter life (Lounis, 1998). Thirdly, there is a lack of understanding for the need of maintenance which leads to neglect in maintenance stage.

Table 2-1 Some Definitions of Maintenance in literature

Researcher	Definition
Panchdhari (2006)	"Work undertaken in order to keep or restore every facility, i.e. every part of a site, building and contents to an acceptable standard".
Bushell (1984)	"a combination of any actions carried out to retain an item in, or restore it to an acceptable condition"
Akasah et al (2009)	"Maintenance is a continuous operation to keep the school buildings, furniture's, and equipment's in the best form for normal use"
Glossary'' 1984	''a combination of any actions carried out to retain an item in, or restore it to, an acceptable condition.''
Seely (1993)	The combination of all technical and associated administrative actions intended to retain an item in or restore it to a state in which it can perform its required functions to an acceptable standard.
Cobbinah (2010)	"The necessary work done to preserve a building with its furnishes and fittings, so that it continues to provide the same or almost the same facilities, amenities and serves as it did when it was first built"
Bin Akasah. (2007)	"Maintenance of a building is a process of reservation and restoration activity of the structure and components of a building."
Korka (1997)	"Maintenance can be defined as the orderly control of activities required to keep a facility in an as-built condition, while Continuing to maintain its original productive capacity."

In fact, the literature shows that increasingly, more emphasis is placed on new construction without adequate attention being paid to the cost of proper maintenance and operation of existing buildings (Johnson and Clayton, 1998). As time passes, deferred maintenance leads to a huge backlog (Singh, 2008). Finally, there is increasing pressure from facility managers to reduce repair costs needed to improve the conditions of a building component.

Throughout a building's lifecycle, in-service maintenance requires continuous funding. Without proper funding, buildings will deteriorate more quickly which results in total failure. The costs of operating, sustaining, restoring, and modernizing a facility to meet performance requirements are not fixed. They depend greatly on the mission being performed, the facility type and size, operational tempo, and the prevailing local rates for energy, water, labor, materials, and equipment (Grussing, 2006). These costs also depend greatly on both the required level of performance, current physical condition and functional capability, and configuration of the facility to meet those requirements (Grussing, 2015).

In order to overcome these challenges, many researchers have proposed various building maintenance management framework to enable facility manager to manage their assets, and maintenance and rehabilitation decisions. The primary objective of these frameworks is the optimization of a building component's life and determining most effective usage.

Facility maintenance management can simply be defined as the process of evaluating assets and choosing the best maintenance strategy and allocation of the available funds among those assets. In most cases, there is a lack of funding and budget constraints force facility managers to find strategies that maximize the condition of their assets with minimum maintenance and rehabilitation costs. However, even in cases where available funds exceed maintenance needs, decisions still need to be made based on what assets should be maintained first and at what year (Cheng, 2016).

Many researchers have noticed that building maintenance management is evolving at a slower rate than management for other assets. There are potentially many reasons for this such as the challenges that face facility manger mentioned earlier, all of which make it very hard to create a framework across the diverse domain of building assets. Paulo (2016) found that because of a larger variety of maintenance problems and a small number of buildings associated with each owner, building management systems are still quite rare. Some infrastructure assets are owned by large companies or federal, state, and local government entities which make it easy to fund maintenance research because these owners are fully aware of the importance of planning for maintenance. Buildings, on the other hand, are mostly owned by private citizens and small companies; small companies tend to not understand and recognize the importance of planning for maintenance (Grussing, 2015).

Good maintenance management can lead to improved facility management as a consequence of being able to demonstrate the links between facility and service goals with the management of assets. It can also improve financial accountability, particularly regarding the effective use of capital for new projects, capital release, and redeployment, and ensure long-term low running costs (Kumar et al., 2010).

According to the literature, the fundamentals to any asset maintenance and rehabilitation management framework should cover the following and as shown in Figure 2.1 and listed below:

1. Assets condition assessment;
2. Assets Deterioration;
3. Maintenance and repair strategies;

4. After-repair condition improvement; and
5. Prioritization of components for repair given budget constraints.

Also, it should be noted that building maintenance should be flexible enough to consider different objective functions based on the facility manager's specific needs and requirements.

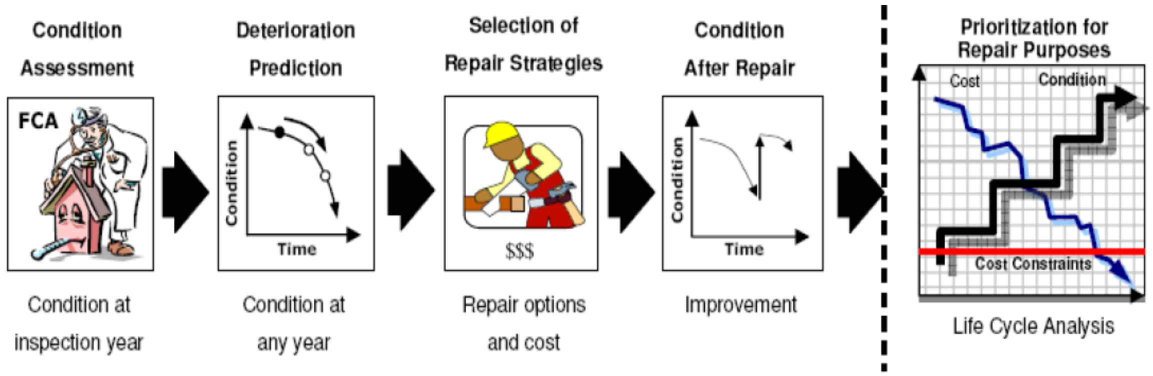


Figure 2-1 maintenance optimization steps (Elhakeem 2012)

2.3 Condition assessment

Condition assessment is the most important stage in an asset maintenance management framework because it is the basis or the starting point of adequate management (Alhuwalia, 2008). It gives an overview or main idea about the health of a building and the criticality of each component, such as which component is more important to maintains than others (Kermani, 2016) and forms the basis of other functions such as future deterioration and the prioritization and optimization phase of maintenance and rehabilitation. Also, an asset maintenance management framework is important to determine the level of repair, replacement, and budget needed (Eweda, 2012). Furthermore, it can give owners and facility managers an impression of current and previous maintenance decisions and plans (Kumar, 2013).

It is very difficult to explain a failure of a component without condition assessment and an asset maintenance management framework can give answers when a component fails. For example, it is suggested the component Fails when it reaches 40 (no longer serviceable) (Stephanie, 2017). Building condition assessment can be handled by different parties such as contractors, in-house staff, and specialized inspectors (Alhuwalia, 2008).

The widest used indication of facility conditions is facility condition assessment (FCA) which Rugless (1993) defined as “a process of systematically evaluating an organization’s capital assets to project repair, renewal, or replacement needs that will preserve their ability to support the mission or activities they are assigned to serve” .

Some obstacles to accurate building condition evaluation is lack of information available about the facility such as missing as-built drawings, organization specification requirements for the facility, lack of a previous maintenance-work database, and poor quality of past inspector & inspection reports (Motawa, 2013). Thus, it is extremely important to have a well-trained inspector. Current studies are trying to propose more efficient techniques and methods for effective condition assessment. According to Elhakeem (2005), when developing an evaluation mechanism for building, four aspects should be developed as shown in Figure 2.2:

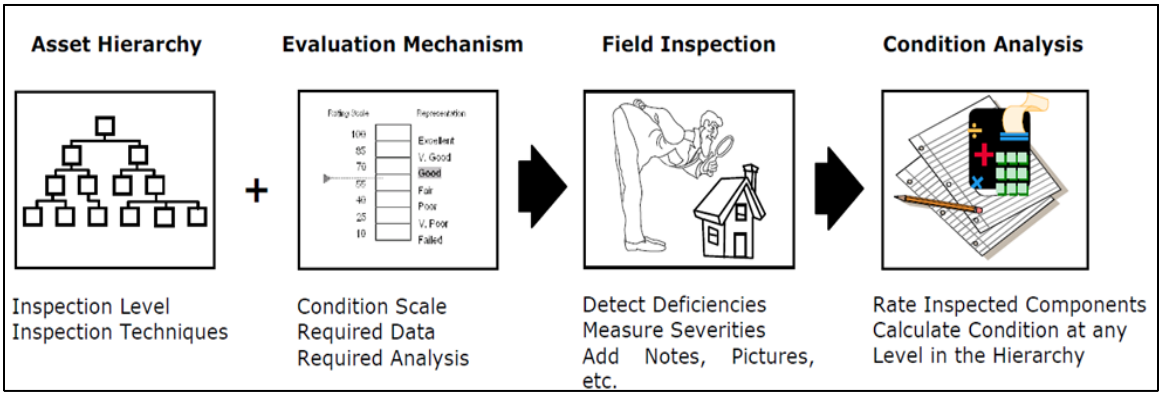


Figure 2-2 condition assessment main steps (Alhuwalia, 2008).

A building's evaluation of state of health can be performed in one of two ways: bottom-up or top-down (Claridge et al., 1999; House and Kelly, 1999). The bottom-up approach evaluates buildings from a component level, analyzing the state of health of each individual system and its subcomponents. The top-down approach applies whole building diagnostics. Each method has its own advantages and disadvantages.

2.3.1 Asset hierarchy

The International Infrastructure Management Manual (IIMM) (2006) states that an asset manager should be fully aware of their asset hierarchy before making any decision or data collection about their assets. Such a hierarchy model defines the level of information required to manage information and decision-making. A detailed flexible hierarchy model can assist in informing managers about risks in detail and the possible effects on the overall delivery of services. Building asset hierarchy (BAH) is defined as a deliverable-oriented grouping of building elements and system, which organizes and defines the entire building. Each descending level represents an increasingly detailed definition of a building system (Uzarski and Burely, 1997).

Hegazy (2001) proposed a hierarchy within the domain of building information modeling (BIM). Their hierarchy involves the creation of a building project hierarchy (BPH) from a central library of building components. This hierarchy has proven useful in representing multidisciplinary design data within each building space. Elhakeem (2005) proposed a BAH that depends on five-levels (system, subsystem, component, type/element, and instance).

Uzarski (2007) proposed a BAH where a building is divided into its main system and component to component section, as shown in Figure 2.4..According to Eweda (2012), none of the previous research has considered the space type in the asset hierarchy process. This thesis accounts for this gap in research, addressed in more detail in Chapter 3.

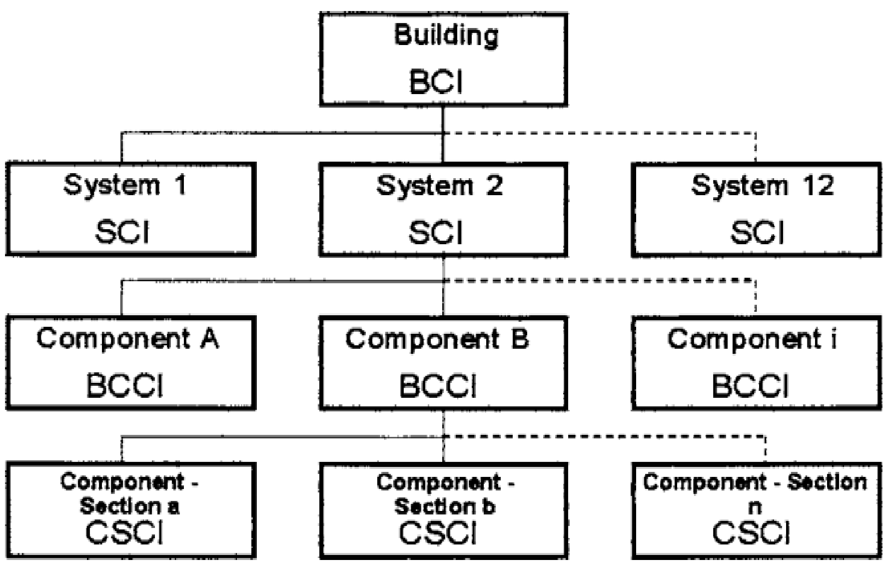


Figure 2-3 Uzarski proposed asset hierarchy (Uzarski 2007)

2.3.2 Evaluation mechanism.

There are two main methods that can be used to evaluate the condition of any component inside a building: a distress survey and a direct-condition rating survey and either or both can be used (Uzarski, 2002). The direct-condition survey entails a visual inspection of each component evaluated based on a set of criteria. Meanwhile, a distress survey provides a record of what is needed to be repaired in the inspected instance (Uzarski, 2002). The two approaches are used by many facility managers. Direct-condition is very simple and gives a quick overview of the overall condition of a building, while the distress survey is a better fit when the reason for the survey is to identify current problems and failures in a system or a component. After a survey has been conducted, an evaluation of the building state for condition assessment can be performed either bottom-up or top-down (Claridge et al., 1999; House and Kelly, 1999). The bottom-up approach evaluates buildings from a component level, considering each individual building systems' and its subcomponents' state of health. The top-down approach applies whole building diagnostics.

2.3.3 Inspection Process and Data Collection.

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

Condition analysis is the last step after the inspection and data collection process has been completed. Usually the inspection process provides data in the form of measurements of instants condition (a component is collections of instants) but in order for this data to translate into condition values, analysis should be conducted. Once a condition value has been calculated for a component, this value can be used to calculate the condition at any level in the asset hierarchy—a procedure called condition aggregation (Ahluwalia, 2008).

2.4 Deterioration

Any human-made product, from simple products to complicated structures, has certain unreliability and deteriorates with time (Murthy et al., 2004) causing adverse effects on various building system functions. The deterioration processes depends on several factors such as the local environmental factors, use and abuse, and levels of routine maintenance accomplished (Grussing, 2015), as well as initial design flaws and improper management (Fouial, 2017). The importance of any deterioration model is its ability to predict the future condition of an asset or any of its components with time. This helps the facility manager predict the best time to replace a component and also gives the facility manager an idea about the most efficient point of where corrective action should be considered or performed. Unfortunately, the complexity of any deterioration model is due to unseen future parameters other than age that can affect the deterioration of a component, the lack of historical data that the asset manager needs to predict the future states of an asset, and the unevenness in deterioration even between identical components. In addition, a building is not a single entity; it is made up of multiple systems that may or may not rely on each other and work together in order to allow the building to perfume its function (Alley, 2015).

Many deterioration models can be found in the literature. Some of these models are simple and limited in their applications, while others are comprehensive and suitable for a wide range of applications (Haas et al., 1994; Lytton, 1987), as shown in Table 2.2.

Table 2-2 Deterioration model

Deterioration	Deterministic method	Stochastic Models
Technique	Straight-Line Extrapolation	Markov model
	Factor method	Weibull distribution
	Regression methods 1- Linear 2-Polynomial 3-Exponential	Gamma distribution
		Artificial intelligent
		Dynamic Bayesian networks

2.4.1 Deterministic Models

Deterministic methods are based on the assumption that the deterioration processes is deterministic (future condition is known with certainty). Deterministic models vary from simple straight-line extrapolation to regression analysis models.

2.4.1.1 Straight-Line Extrapolation Models

Straight line is the simplest method among all deterioration methodologies. Straight line uses statistical data available from condition inspections and groups together components with the same attributes. Then, within each group, it draws a straight line between two points in time with the same known condition to extrapolate the future condition at any time to a third point (Semaan 2011) as shown in Figure 2.5.

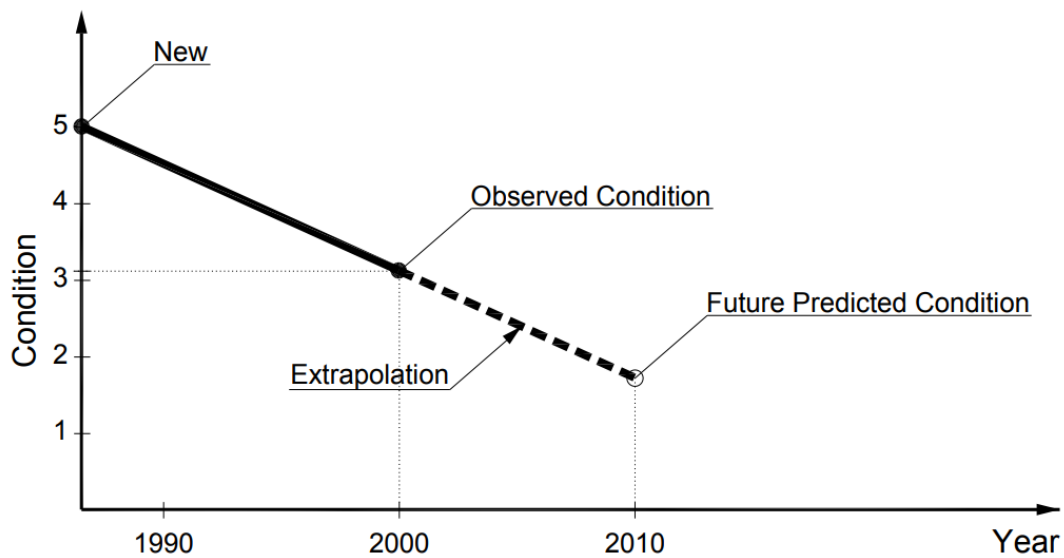


Figure 2-4 Straight-Line Extrapolation deterioration Model (Semaan 2011)

It should be noted that a limitation of the straight line method is that it fails to represent the stochastic nature of the deterioration process. As such, it is not a reliable deterioration prediction method (Tran, 2007).

2.4.1.2 Factor method

Factor method is another deterministic method for service life prediction based on Standard ISO 15686-1 (2000), which is described by the following formula (Marteinsson 2003).

ESLC = RSLC x factor A x factor B x factor C x factor D x factor E x factor F x factor G.

Where:

RSLC is the reference service life of the component

Factor A: quality of components. Where it is a measure of the quality of design material of component when supply to the site.

Factor B: design level, design level is the level of protection of the component by the design in terms of installation.

Factor C: work execution level, Factor D: indoor environment is the measure of the severity of internal deterioration reasoners.

Factor E: outdoor environment is the measure of the severity of outdoor deterioration reasoners.

Factor F: in-use conditions. Is a measure of the functionality of the space and occupants?

Factor G: maintenance level is the assessment of previous maintenance.

These factors can be summarized as shown in table 2.3

Table 2-3 Factor described by factor method (Marteinsson 2003)

Agents	Factor	Relevant condition (examples)
Agent related to the inherent quality characteristic	A	Quality of components (manufacture, storage, transport, materials, protective coating (factory applied)
	B	Design level (incorporation, sheltering by rest of structure)
	C	Work execution level (site management, level of workmanship, climatic conditions during execution of work)
Environment	D	Indoor environment (aggressive environment, ventilation, condensation)
	E	Outdoor environment (elevation of building, microenvironment conditions, weathering factors etc)
Operation conditions	F	In-use conditions (mechanical impact, category of users, wear and tear)
	G	Maintenance level (quality and frequency of maintenance, accessibility for maintenance)

2.4.1.3 Regression methods

Empirical (regression) is a more accurate method when compared to the straight line and is the most popular method for developing deterioration models; however, regression models require careful examination to ensure they are realistic (Mubaraki, 2010) as they depend on creating a function that represents the relationship between variables. This relationship could be linear, polynomial, Sigmund, exponential etc., as shown in Figure 2.6.

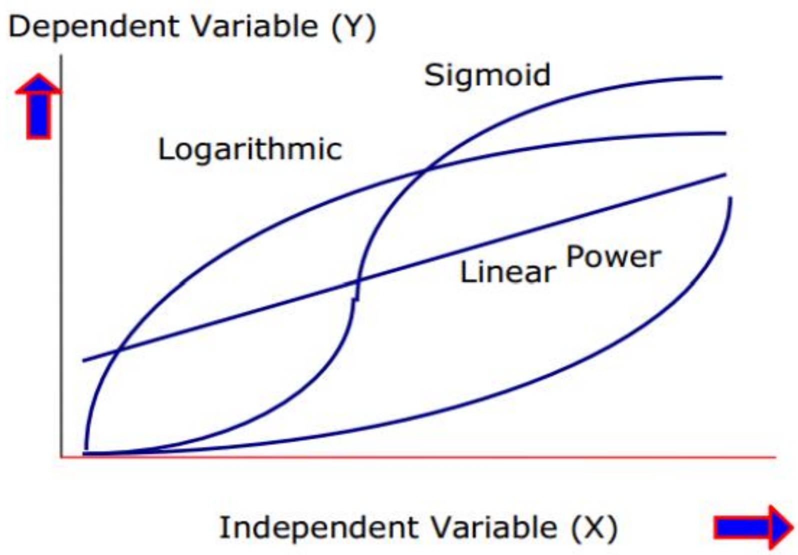


Figure 2-5 Typical deterioration Regression Curves. (Mubaraki 2010)

Regression models are calibrated using statistical data available from condition inspections to group the components with the same attributes together. Then, within each group, a fit equation is drawn and calculated to represent data. Deterioration calculations can be represented as linear, polynomial, and exponential.

Another type of equation is the sigmoid function. Hunt and Bunker (2001) and Mubaraki (2010) argue that the sigmoid model is the best fit for deterioration prediction of infrastructure. The sigmoid function can be represented as:

$$S(t) = \left(\frac{1}{1+e^{-t}}\right) \qquad \text{Equation 2-1}$$

It should be noted that deterministic models have certain drawbacks that can be summarized as follows. Firstly, these methods neglect the inherently stochastic nature of infrastructure deterioration and existence of unobserved explanatory variables and thus, cannot account for data uncertainty (Madanat et al., 1995; Jiang and Sinha, 1989). Secondly, they do not consider current conditions and the condition history of individual facilities when predicting the average condition of a family of facilities (Shahin et al., 1987; Jiang and Sinha, 1989). Furthermore, the interaction between the deterioration mechanisms of different facility components such as between the bridge deck and deck joints is also not considered (Sianipar and Adams, 1997). Finally, these methods fail to represent the stochastic nature of the deterioration process. Thus, regression models do not represent a reliable approach for deterioration prediction (Tran, 2007). Furthermore, regression models are hard to update with new data (Mohsenim, 2012) and fail to estimate the no maintenance future condition because it's difficult to estimate the after-repair condition (Sanders and Zhang, 1994).

2.4.2 Stochastic Models

Deterioration is a dynamic process subject to a lot of uncertainty which happens from the simplistic representation of the actual physical processes and from limited information available on materials and environmental conditions (Straub, 2009). Unlike the deterministic method, stochastic models (probabilistic methods) predict condition as a probability of occurrence of a range of possible outcomes (Scherer, 1994) making them superior when compared to deterministic models. In term of prediction technique, the stochastic method can be divided into two categories: time-based and condition-based (Albrice, 2015).

In the time-based category, the model predicts the time needed by the building component to change its condition. Meanwhile, condition-based models predict the probability that a facility will undergo a change in condition state at a time. It should be noted that Markovian models are the most commonly used models in the probabilistic method (Elhakeem, 2005). Even Markovian models suffer from the lack-of-memory. Probability of any future state is completely independent of the current or past states (Farran, 2006).

2.4.1.1 The Markovian model

Just like all stochastic models, the Markovian model assumes deterioration is a stochastic process that changes with time. The Markovian model analyses deterioration as a stochastic process governed by random variables, where the structure can be split into a number of randomly deteriorating components. The main parameters of deterioration are established for each component, together with the deterioration variables versus time (Zhang, 2005). The general equation in the Markovian can be given by in matrix form:

$[ST_t]_{1x1} = [IP_0]_{1xn} . [TPM]^t_{nxn} . [PS]_{nx1}$ Equation 2-2

Where:

$[ST_t]_{1x1}$: the predicted state (ST) at any time (t)

$[IP_0]_{1xn}$: the Initial Probability matrix IP_0 is a row matrix, which represents the initial state of the component

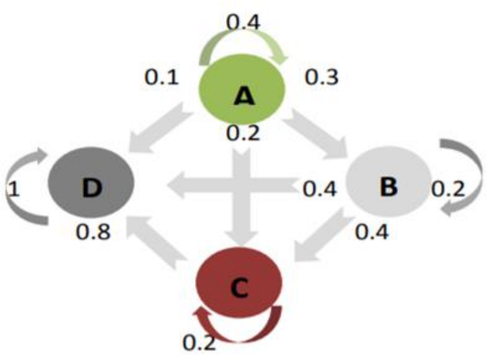
State [1 2 3……………n]

[IP0] = [1 0 0 0]

[TPM] t nxn : transition probability matrix formulated as

$$\text{TPM} = \begin{bmatrix} p_{1,1} & 1-p_{1,1} & 0 & 0 & \dots & 0 \\ 0 & p_{2,2} & 1-p_{2,2} & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & p_{i,j} & 1-p_{i,j} & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & 1 \end{bmatrix}$$

The TPM matrix cab be graphically represented as figure 2.7.



	State A	State B	State C	State D
State A	0.4	0.3	0.2	0.1
State B	0	0.2	0.4	0.4
State C	0	0	0.2	0.8
State D	0	0	0	1

Figure 2-6 typical TPM matrix (Keshavarzrad 2015)

Each row and number represent the probability that a building component will change its state. For example, in the above equation there is a 0.1 probability that a building component will change its state from state A to state D and so on. The transition matrix here states that the building component cannot move to a lower state from a higher state at any given time. The sum of the rows is always one and the model cannot incorporate the rehabilitation impact in the model calculation.

According to Mohisine (2012), the TPM matrix should satisfy two conditions.

1. $pij \geq 0 \; for \; i, j = 1,2, \dots \dots, k$
2. $\sum_{j=1}^{k} pij < 1$

From the above equations the most important step is to calculate the [TPM] matrix.

The simplest TPM calculation process is the percentage prediction method used initially for the data set in which two consecutive data sets of the same components were acquired. Probability 'Pij' of a transition from state 'i' to state 'j' in a component's condition can be estimated using the following equation (Jiang et al., 1988):

$$Pij = \frac{nij}{ni}$$ Equation 2-3

Where

nij: is the number of transitions from state 'i' to state 'j' within a given time period

ni: is the total number of components in state 'i' before the transition.

2.4.1.2 Weibull distribution

In the field of probability and statistics, the Weibull distribution is one of the most commonly used methods for predicting failures, malefactions, and modeling data reliabily. The distribution is named after Waloddi Weibull who discovered it in 1937 and delivered his work in 1951. Weibull stated that its distribution applies to a wide range of problems and demonstrated this with seven examples ranging from the strength of steel to the height of adult males in Great Britain. The advantages of model are that it shows acceptable failure analysis and forecasts failure extremely well with a small sample and has the capability to produce a simple failure data graphical plot, all of which is very important to engineers and managers (Nassar, 2017). In addition, it is flexible enough to model a variety of data sets and to hazard functions that are decreasing, increasing, or constant, allowing it to describe any phase of an item's lifetime (Martinez, 2006).

The cumulative Weibull distribution function (cdf) is defined in Equation

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$ Equation 2-4

Condition and reliability are proportionally related. For example, if a component with a CI of 90 is expected to have a higher probability of reliably performing than a component with a CI of 60, then CI of 60 has a higher chance of breakdown or failure .According to Grussing (2006), reliability is “the statistical probability that a Component section will meet or exceed performance requirement for a given length of service.” The relation between condition and reliability can be summarized as follows:

1- The reliability and condition are maximum at or near the start of the service life.
2- The reliability and condition approach the minimum state asymptotically.
3- Reliability and condition deteriorate unless an action is performed to stop the deterioration.
4- As condition degrade, the reliability decrease.

Since the reliability function of a distribution is simply one minus the Cumulative Distribution function (cdf). The reliability function for the Weibull distribution is Given by Equation

$$R(t) = 1 - F(t) = e^{\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$ Equation 2-5

According to building condition prediction models (Grussing et al. 2006) The Weibull cumulative probability distribution function can be defined as:

$$C(t) = a * e^{-\left(\frac{t}{\beta}\right)^{\alpha}}$$ Equation 2-6

Where

C (t) = component section index as a function of time

t= time in years

e= exponential

β= service life deterioration factor

α= accelerated deterioration factor

2.5 Assets Prioritization for repair purpose

2.5.1 Assets prioritization based on ranking

Prioritization ranks items based on their weight, importance, criticality or significance. Prioritization is very important since it helps the decision maker find the most critical item that should be focused on under budget limitations. According to Shen (1998), budgets for building maintenance are not likely to meet ever-increasing maintenance costs and as such, there is a need for maintenance plans based on wise judgment. Prioritization is a subjective process; there is no clear right or wrong order by which to prioritize, which causes difficulty and miscalculations. Some of the prioritization practices found in the literature are described below.

Spedding et al. (1994) introduced the application of the multi-attribute in the priority setting of maintenance. According to Spedding et al. (1994), building maintenance managers should deal with six factors before making a maintenance decisions: technical, political, financial, social, economic, and legal, as shown in Figure 2.8. In this method, each criteria is ranked and weighted according to their relative importance. Maintenance works identified during the inspection are measured and a score is given in respect of each criterion. Suppose criteria C1, C2, …, Cp, …Cn are used and their relative weights are W1, W2, …, Wp, …, Wn and work j scored Sj1, Sj2, …, Sjp, …, Sjn against criteria C1, C2, …, Cp, …, Cn, he overall priority index for job j should be calculated using the following formula:

$$Sj = Sj_1 * W_1 + Sj_2 * W_2 + \cdots + Sj_p * W_p + \cdots + Sj_n * W_n$$

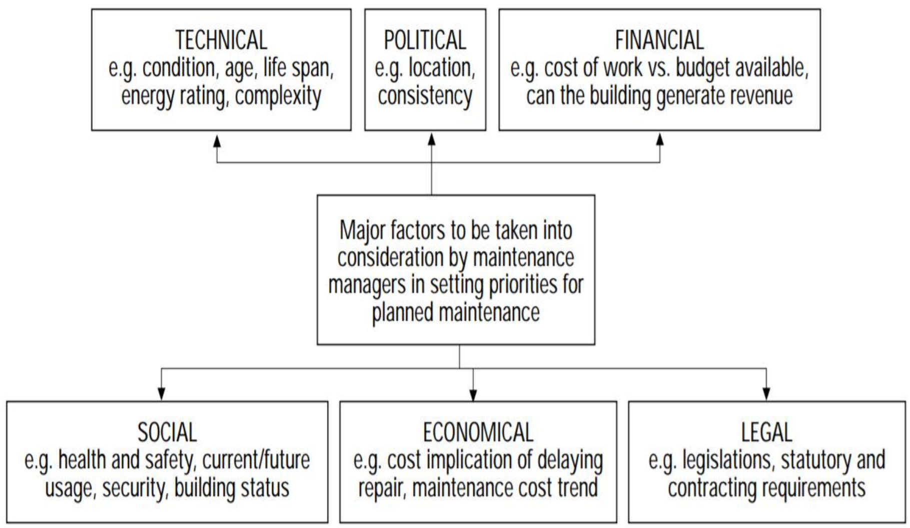


Figure 2-7 factors to be considered in planned maintenance prioritization (Spedding et al. 1994)

Spedding (1994) used six criteria as follow:

1- Building Status (BS): The relative importance of the building
2- Physical Condition (PC): The physical condition of the defective element.
3- Importance of Usage (IU): The importance of the functional unit (in relation to other units within the same building).
4- Effects on Users (EU): The effects of the failure of an element(s) on the occupants and users of the building.
5- Cost Implication (CI): The cost implication of breakdown or failure of the defected element(s) on maintaining the overall condition of the building services.

6- Effects on Service Provision (ESP): The cost implication of breakdown or failure of the defected element(s) on the provision of services.
   This method takes in to account other secondary criteria such as legal requirements, special maintenance policies, and pressures created from day-to-day maintenance.

Chui (2009) found many advantages of this method such as that the resulting priority considers the maintenance policy of the organization and the induvial condition of the job. This framework has also been tested with actual data in an existing maintenance program and the effectiveness of the criteria was backed by maintenance managers.

Shohet (2003) establish an evaluation methodology to link the building performance indicator to set the priority of building system in the allocation of recourses, by using his methodology it is possible to set the priority based on the performance of the entire building, and on the performance of each system in the building.

Shohet (2003) established an evaluation methodology to link the building performance indicator (BPI) and the setting of building system priority in the allocation of recourses. By using his methodology, it is possible to set priority based on the performance of an entire building and on the performance of each system in the building. This building evaluation methodology uses systematic rating scales for the evaluation of building component performance. The condition of the entire building is determined based on BPI, which is composed of the weighted average of the scores given to the various building systems. The weight of each system in BPI is derived from its respective value in the life cycle costs of the building. The condition of building components is evaluated according to three criteria: physical performance of systems, frequency of failures in building systems, and actual preventive maintenance carried out on the systems.

Table 2-4 Pairwise Comparison - Saaty's Fundamental Scale

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Abdullah (2012) suggest a very simple and straightforward way to prioritize maintenance work in public housing based on the user. According to Abdullah (2012), resident involvement in priority setting of building maintenance improves the decision-making process. They conducted face-to-face surveys with the residents of the building in order to determine priority in maintenance work. Abdullah’s (2012) results are shown in table 2.5 and the resident maintenance priority preferences in table 2.6.

Table 2-5 Reasons for Maintenance (Abdullah 2012)

Reason for Maintenance	Mean	Standard Deviation	N
Work necessary to maintain the safety and health of residents	1.07	0.260	398
Work necessary to keep property habitable	1.26	0.439	398
Work necessary to keep buildings operable	1.37	0.483	398
Emergency failure	1.40	0.623	398
Preventive maintenance	1.60	0.584	398
Work necessary for the appearance of the property	2.17	0.761	398
Repair of building material	2.37	0.776	398

Table 2-6 maintenance priority references (Abdullah 2012)

Maintenance Priority Preference	Mean	Standard Deviation	N
Electrical faults	1.11	0.387	398
Sanitary appliance failure	1.28	0.475	398
Pipes linkage	1.34	1.141	398
Damaged ceiling	1.42	0.524	398
Damaged internal door	1.52	0.780	398
Floor tile failure	1.56	0.734	398
Damaged floor sheet	1.57	0.665	398
Damaged taps/stop valves	1.64	0.950	398
Damaged door locks	1.64	0.855	398
Blocked drain	1.70	0.843	398
Wall tile failure	1.71	0.915	398
Damaged painting	1.75	0.751	398
Damaged door and windows frame	1.84	1.022	398

2.5.2 Assets prioritization based on optimization

This area is the least developed area in maintenance optimization (Elhakeem, 2005). Optimization can be defined as the mathematical process by which to determine the maximum or minimum in order to obtain the best solution or result. Optimization is very important to engineers and facility managers since, in the construction or maintenance phase of an engineering system, engineers have to make many decisions at several stages and the main objective of these decisions is to maximize the desired benefit. Optimization can be very useful and can be adapted to solve many real-life problems, while optimization of maintenance works during a building's lifecycle reduces resource-use and unnecessary cost (Morgado, 2017).

Lounis and Vanier (2000) combined a stochastic Markovian performance-prediction model with a multi-objective optimization procedure to determine the optimal prioritization of roof sections for a maintenance plan but did not discuss higher-level replacement activities. Condition assessment was based on in-field visual inspection and nondestructive testing, which was based on the evaluation of water tightness, energy control, condensation control, air leakage control, load accommodation, and maintainability.

Elhakeem (2012) proposed a multiple optimization and segmentation technique, which they claim lowers the search space and increases accuracy. This model works by breaking down a large optimization problem into small ones and solving each one individually by decomposing large optimization problem to two phases of optimization. The first phase is best maintenance action optimization for each building component and this is considered input for the second phase which is calculating the best timing for the stage one action by using a genetic algorithm (GA). The model could be considered a special case of bi-level optimization. It should be taken into account that the condition of any building component is based on a detailed field inspection and each small optimization represents a building component.

Binhomaid (2012) compared between heuristic and genetic-algorithm Optimization methods to conclude which one is more efficient in solving fund-allocation among building systems and concluded that the GA proccing time where less compared to a heuristic for the large-scale network. Also Based on his research, when not taking time into consideration, both methods are similar.

Grussing (2015) integrated the condition index (physical condition) with the capability index (the loss functional loss because of obsolescence). An example of capability loss included outdated look, maintainability, and availability of parts, energy efficiency, asbestos materials, lead-based paint, code violations, and outdated floor configuration. The fund allocation problem was solved based on a single-objective GA algorithm using Evolver Decision Tools Suite 6.2 add-in to Microsoft Excel under cost constraints.

Abdelbaset (2013) developed a multi-criteria performance assessment framework for hospital buildings. The main unique feature in Abdelbaset study was dividing the hospital into three zones. Dividing the building into big zones will fall to capture certain spaces which have special requirements and needs. Abdelbaset (2013) argued that the condition or the status of the building system should not be the only factor when considering planning for a maintenance and integrated three other factors: sustainability, level of service, and risk. These four factors make up the base of a maintenance plan. Finally, the allocation of funds were allocated based on GA algorithm using Evolver Decision Tools

Optimization can be classifieds in many ways such as constrained subject to restrictions which are more practical optimization problem and not subject to restriction unconstrained optimization or according to the objective function as linear or nonlinear. another way as traditional (i.e. linear programming) and Modern or nontraditional optimization techniques, One example for the traditional method in maintenance optimization is Farran (2009) who integrate the Markovian model with linear programming to create an optimization model for structural slab in STM metro of Montreal, Farran used three different methods for calculating life-cycle cost (LCC), and the average expected discount cost per time period and continuous rating approach finally a dynamic or time-dependent TPM. And proved that using the continuous rating approach obtained lower a life cycle cost than other methods.

Modern methods of optimization or so-called non-traditional optimization methods are considered effective and reliable methods to solve complicated optimization problems. These methods include GA, simulated annealing, particle swarm optimization, ant colony optimization, neural network-based optimization, and fuzzy optimization. Many mathematical programming techniques, soft computing methods (e.g. GA, particle swarm optimization, etc.) or hybrid models that combine the two techniques have been used in infrastructure maintenance optimization. Mathematically optimization can be represented as:

Find X from $\begin{bmatrix} X1 & \cdots & Xn \\ \vdots & \ddots & \vdots \\ Xm & \cdots & Xmn \end{bmatrix}$

That minimize f(x), where f(x) is the objective function.

A formulation of optimization should start with defining variables.

2.5.1.1 Evolutionary Algorithms

Evolutionary algorithms are a mathematical search method inspired by any natural process to find the near optimum solution when the search space is too wide to be solved using traditional optimization methods (Maher, 2005). The first and most common evolutionary algorithm in infrastructure maintenance optimization is GA (Elbeltagi, 2005). GA is based on the Darwin's theory of survival of the fittest because it has the ability to find ideal solutions to complex and large-scale optimization problems in a single- or multi-objective problem or even if different objective optimization exist (Rao, 2009).

Its main goal is to produce a better group of better solutions by mutation, reproduction, and crossovers. Each solution in GAs is represented by chromosomes the fitness of each chromosome is determined by evaluating it against an objective function then the best chromosomes swap information by crossover or mutation. In mutation, new gene is produced that does not exist in the parents and transfer it to children to produce offspring chromosomes while in crossover Cross over is simply transferring the available genes from parents to children through chromosomes (Ismaeel 2016). The offspring are evaluated to produce the best population and optimization go again until the near optimum solution is found as shown in fig 2.9.

As the population size increases, GA accuracy increases but more time is needed to find a near-optimum solution. Thus, GAs may require long processing time for a near optimum solution to evolve. However, since not all problems lend themselves well to a GA solution, this urged researchers to develop other evolutionary algorithms such as particle swarm, ant colony, bee colony, shuffled frog leaping (SFL), and artificial immune system (Yu, 2010).

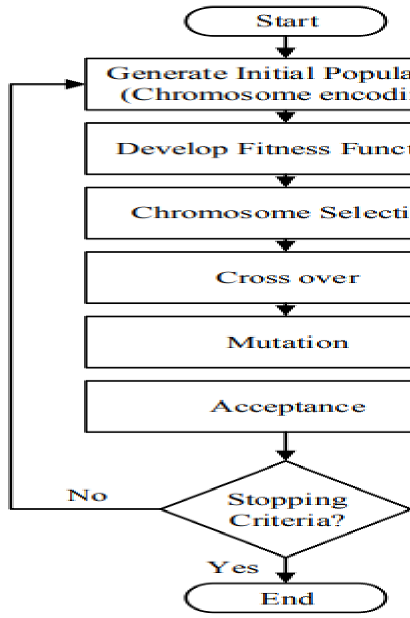


Figure 2-8 Basic Genetic Algorithm Flowchart (Abouhamad, 2015)

Four main guidelines affect the performance of GAs:

1-Population size.

2-Number of generations.

3- Crossover rate.

4-Mutation rate.

Marco and Dorigo (1992) developed the ant colony optimization algorithm (ACO). ACO simulates the ability of the ant to find the shortest path to food. Ants use pheromones trails to find food and these pheromone trails act as a form of indirect communication, deposited on the ground whenever an ant travels to find food. The ants with the shortest path are able to return faster to the nest and leave more pheromones on their trials. This gives new ants that have just started searching an indication that these trials are the fastest way to find the food, and eventually, more and more ants follow the shortest path (Dorigo, 1997). The ant colony method can be represented graphically as shown in Figure 2.10.

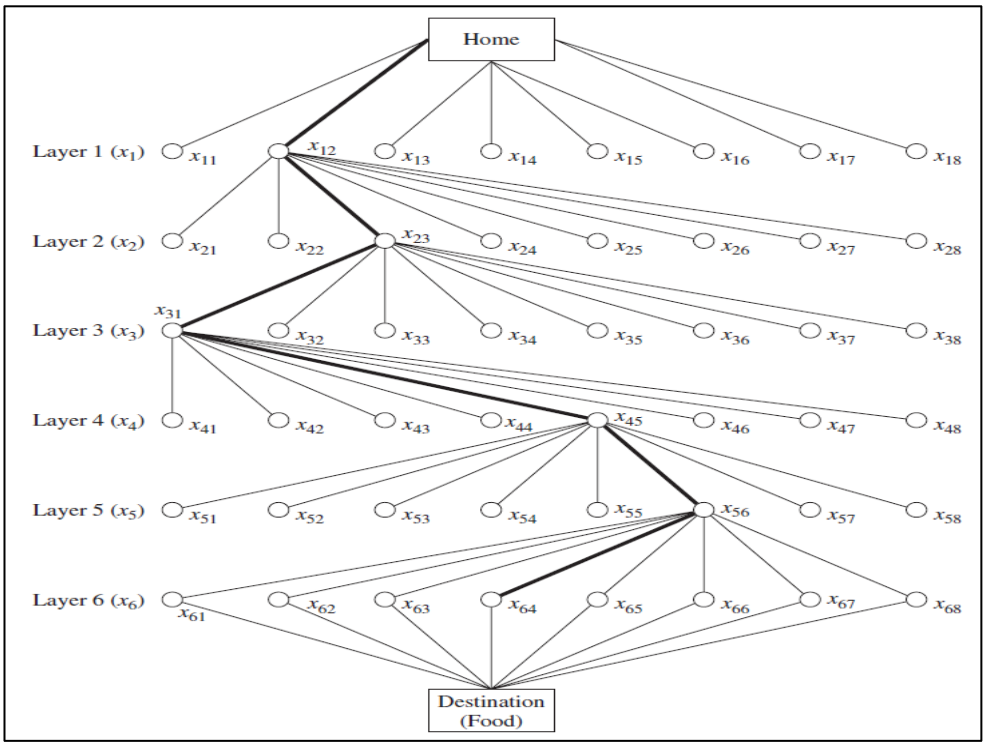


Figure 2-9 Graphical representation of the ACO process (Rao 2009)

2.6 Summary and Limitations of Previous Research Works

So far, the various techniques to prioritize and optimize maintenance work in buildings have been discussed. The following limitations were derived:

1. Previous maintenance optimization model did not consider the space type and the type of the task held are ignored. Optimization models' main objectives are to improve the condition of the building system, but they disregard and do not consider the space type.

2. Asset prioritization models based on simple ranking do not consider the year by year or the lifecycle costs.

3. Most of the previous researches utilize a single objective optimization to optimize the maintenance plane of the buildings, either maximizing the building condition or minimizing the cost. This method results in only one optimal or near-optimal solutions in a single run, which does not provide the decision maker with much flexibility in the selection of the trade-offs alternatives. Moreover, the decision maker cannot track the impact of an objective on the others. The decision maker will be able to monitor the condition of the component along the study when using multi-objective optimization.

Chapter 3: Methodology

3.1 Overview

Chapter 2 reviewed some of the strategies, techniques, and methods that were used by previse researchers to optimize rapier actions of assets. This chapter outlines the research methodology adopted to optimize such assets.

Despite the great historical, cultural and economic importance of public buildings, there are signs that they are deteriorating and in an unsatisfactory condition due to age, harsh environmental conditions, insufficient capacity, lack of funds and poor or mismanagement (Ali 2013). According to (SHEN 1998) budgets for building maintenance are not likely to meet the ever-increasing maintenance cost. So, there is a need for a maintenance plan which is based on a wise judgment. Maintenance prioritizations model is a way to tackle this problem.

3.2 The main Concept of Proposed Methodology

The first necessity for the optimization model is the asset hierarchy because buildings is a complex collection of smaller systems and parts and the rehabilitation activities are usually applied to those smaller parts. Picking the right type of action and timing against the objective of the facility is how the optimization work. A building can be grouped into assemblies that have the same physical characteristic from which it is made such as material or it can be decomposed to spaces inside the building that have the same function. Space could be a room, a group of rooms, a corridor, etc.

Spaces can be further grouped into areas. In an incremental sense, considering just a small portion of the building and the elements that serve it, the objective is to manage the condition of the elements by applying rehabilitation actions (repair, replace, etc.), such that the service to the space they serve is maximized. Asset management for an entire facility requires this maximization to occur across all the spaces of a building, which would in turn, consider rehabilitation work for all the components of the building. An overview of the methodology could be found in Figure 3.1.

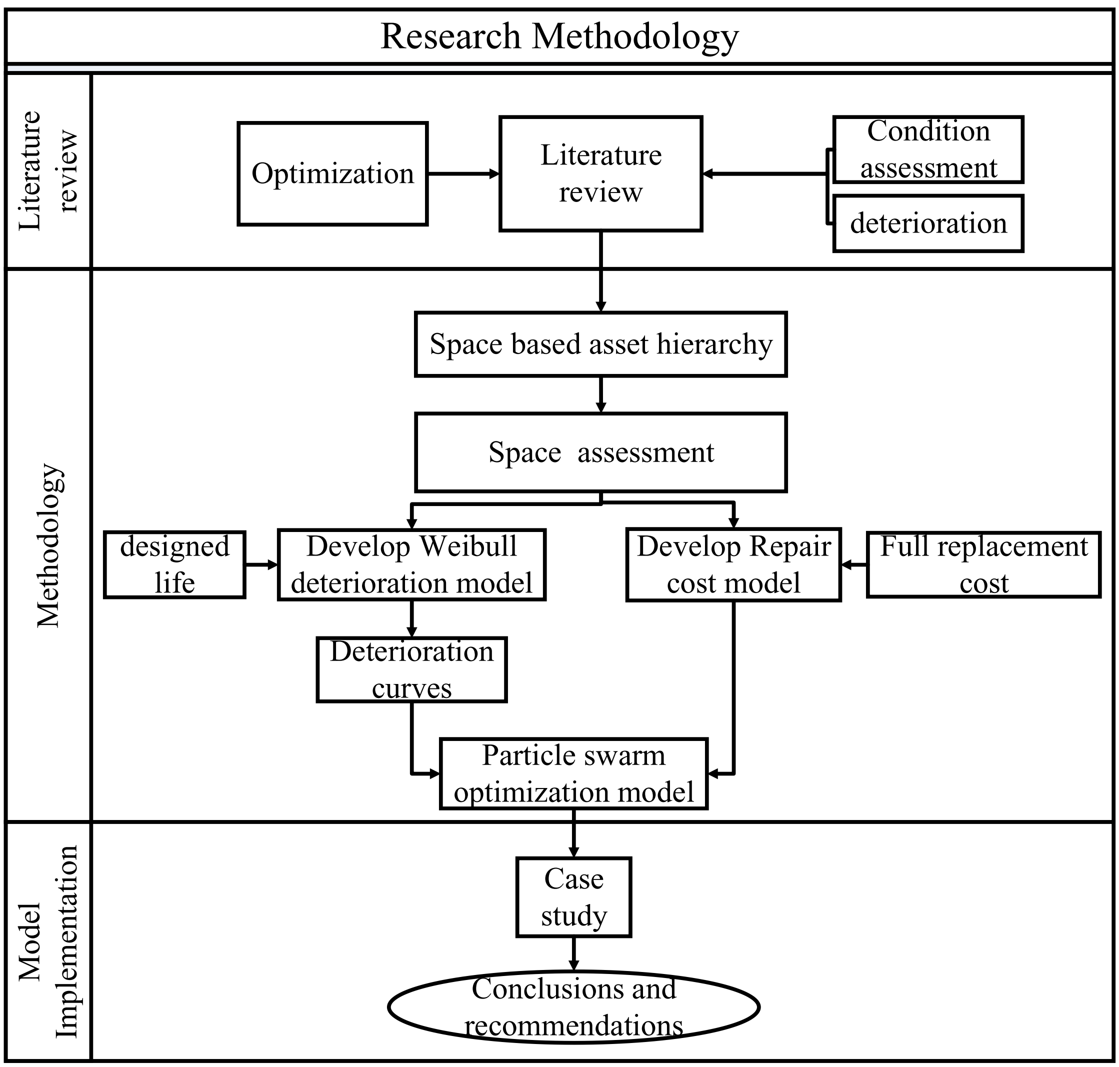


Figure 3-1 methodology overview

3.3 Space -based model

The first step in developing an optimization model is the evaluation of the current condition of the building .One important step is the building asset hierarchy due to the fact that buildings are composed of complex systems that consist of smaller parts and splitting these systems by using asset hierarchy make it easier to deal with building complexity. The condition assessment used in the proposed optimization model was developed by Ewada (2012). It uses a scale from 0 to 100 for building elements, which is sufficiently wide to describe a suitable range of component conditions in which 0 corresponds to the best condition (like new), and assumes that building components are serviceable until the condition rating reaches a value of 80 (non-serviceable). The space ranking is shown in figure 3.2.

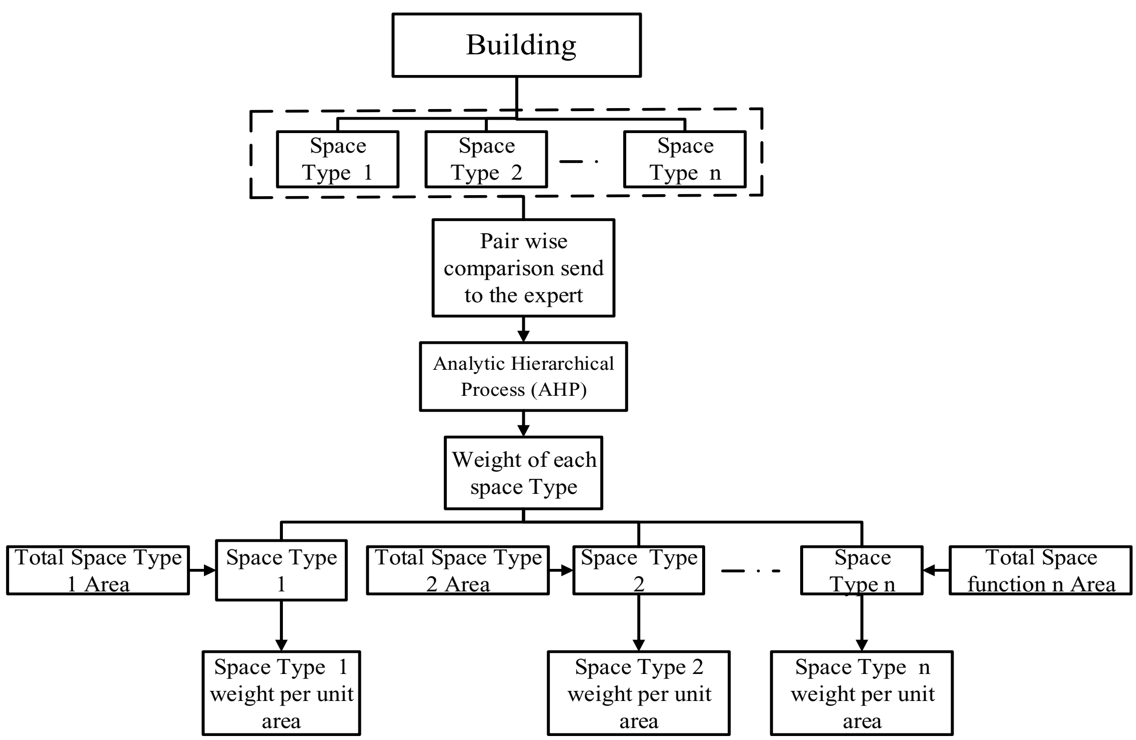


Figure 3-2 Space-based ranking (Ewada 2014)

Ewada (2012) building asset hierarchy will be discussed in detail in the following sections.

3.3.1 Space-based Asset hierarchy for buildings

The first step is the arrangement of functional analysis of spaces inside the building where hierarchical scheme to list the spaces and systems inside them according to their space function in the building. The space-based asset hierarchy is shown on figure 3.3. Six level hierarchy starting from the building level which is a description of building type or function that is different from building to other. The second level is the space level where two pieces of information, the space area and space type, are found. The third level is a representation of main building disciplines inside the space. In this research, the focus will only be on the architectural category.

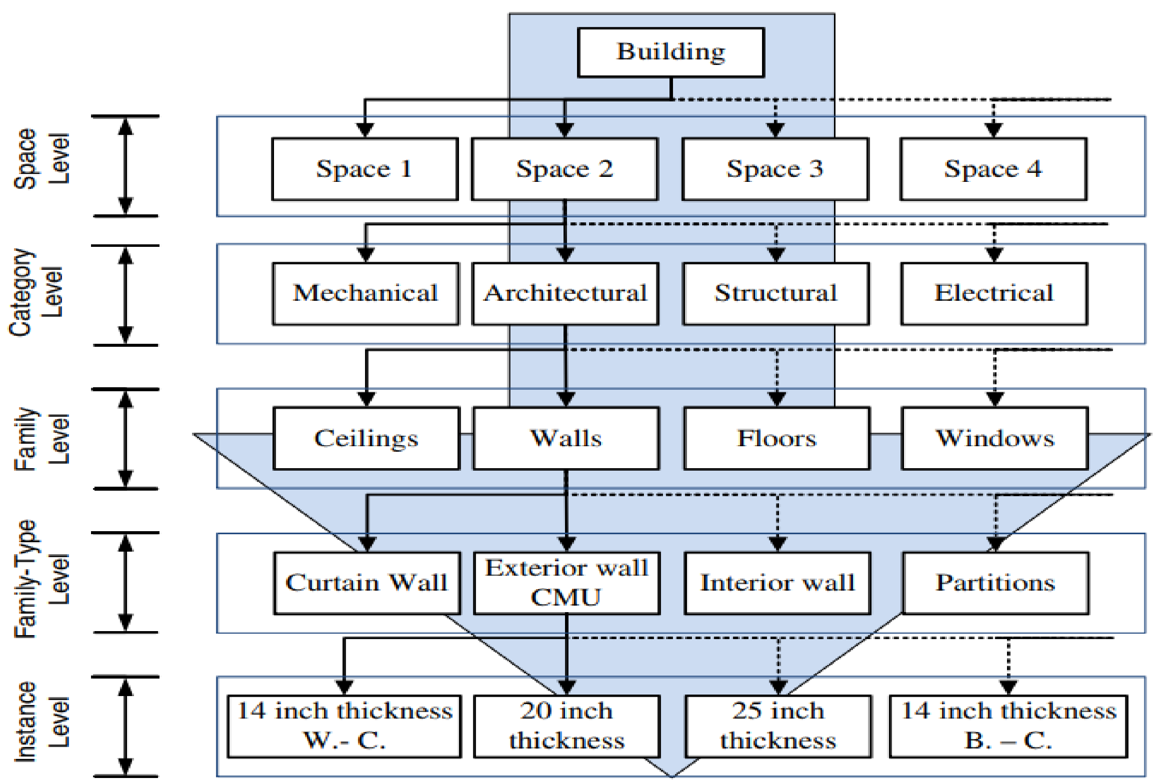


Figure 3-3 Space-based asset hierarchy (Ewada 2014)

3.3.2 Physical condition of each space

The second step after the analysis of the spaces is the identifying the relative importance of each space type inside a building which can be done through the AHP with the survey sent to experts. Also, the number of spaces and the surface areas affect the relative weight of each space inside the entire building. Thus the weight for each Space can be given by:

$$Spw_i = \left[\frac{Sp(Qspt_i) \times SP(Arp_i)}{\sum_{i=1}^{I}[SP(Qspt_i) \times SP(Arp_i)]}\right] \times Spa_i \qquad \text{Equation 3-1(Eweda 2013)}$$

Where:

SPw_i: Weight of selected space.

$SP(Qspt_i)$: is the weight of the space type calculated from the questionnaire.

$SP(Arp_i)$: Area space type percentage.

$\mathrm{Spa_i}$: $space\ i\ area$

Each space weight will have its impact on the maintenance plane. Based on equation 3.1 the contributing factors which determine the space weight are the area of the space and the space type. These factors make the optimization model more flexible than other models found in the literature since it takes and treats each space individually. In this thesis, an optimization model will be developed for the architectural system which are found in a building. The final level of the condition is the overall Building condition which is the sum of the multiplication of the space weight by the corresponding condition (equation 3.2).

$$BCI = \sum_{i=1}^{I} Sp_{wi} \times Sp_{CI_i} \qquad \text{Equation 3-2 (Ewada 2013)}$$

Where:

Spw_i: $space\ i\ weight$

Spw_i: $space\ i\ condition$

The selected space condition on the other hand is the sum of the multiplication of the system weight inside the space by the corresponding condition (which can be calculated using Weibull deterioration model discussed in section 3.4). Mathematically can be represented by equation 3.3.

$$Sp_{CI} = \sum_{j=1}^{J} Sy_{w\,j} \times Sy_{CI_j} \qquad \text{Equation 3-3}$$

$\mathrm{Sy}_{\mathrm{w_j}}$: $system\ j\ weight$

$\mathrm{Sy}_{\mathrm{CI_j}}$: $system\ j\ condition$

The system condition in each space also can be calculated based on the multiplication of the defect weight by the defect severity.

$$Sy_c = \sum_{k=1}^{K} Dw_k \times Ds_k \qquad \text{Equation 3-4}$$

3.4 Weibull Deterioration model

A deterioration model to predict the future condition of buildings system in time forms is a fundamental part of any maintenance optimization model (Van 2013), because Maintenance activity along with actions will only be useful if the asset manager manage to determine deterioration rate and the future decline in the condition of the building so that an appropriate maintenance and rehabilitation strategies can be selected which lead to the reduction of maintenance cost (Sobanjo, 1997).

In a successful deterioration model, the data which the deterioration model provides for the degradation processes should match the real degradation of the building. Moreover, deterioration models should incorporate the contribution of the most effective variables. In facility management condition or performance, prediction is not easy considering that buildings is not one single entity, buildings consist of many components that have a different service life. For example, most structural components have very long service life while on other hands a component like a lamp has a small service life. In this research, Weibull Analysis is used for the deterioration of the building component. This approach has been used in the past for various building components (Grussing et al. 2006). For many building components in their early life performance or maximum condition is at the top then they start to deteriorate, Weibull distribution can easily represent such a situation.

One of the main advantages of the Weibull approach is the fact that its parameters can be computed using only two pieces of information the age and the current or initial condition of the component. Other commonly used methods, required the input of larger amount of data, thus making their development more time-consuming. From the literature review, the Weibull reliability function can be given by equation 3.3.

$$CI(t) = \alpha \times e^{\left(\frac{t}{\tau}\right)^{\delta}} \qquad \text{Equation 3-5}$$

Where:

CI = system condition

t = known, the difference between inspection and construction years

α = initial condition

τ = scale parameter

δ = deterioration/slope parameter

These parameters can be solved based on the assumptions as follows:

At time t = 0,

The CI=100 (maximum condition)

$100 = \alpha \times e^{\left(\frac{0}{\tau}\right)^{\delta}} = \alpha \times 1$

So

$\alpha = 100$

At time = SL, CI= (minimum condition),

$\text{mCI} = 100 \times e^{\left(\frac{service\ life}{\tau}\right)^{\delta}}$

$\text{mCI} = e^{\left(\frac{service\ \ life}{\tau}\right)^{\delta}}$

$$\tau = \frac{service\ life}{\sqrt[\delta]{-\ln(\frac{\text{mCI}}{100})}}$$

$\delta = 3$(to give the desired shape) Semaan (2011)

The typical deterioration carve can be shown in fig 3.4.

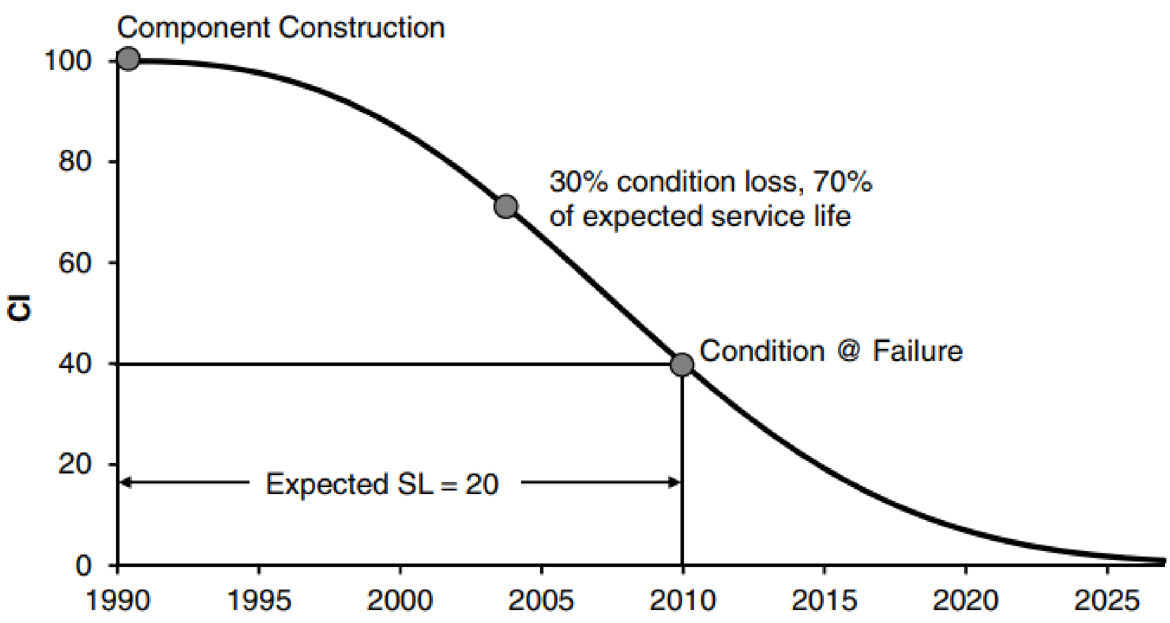


Figure 3-4 Typical deterioration curve (NGSMI 2002)

Another advantage, and actually one of the strong points, of the Weibull model is the ability to update its curve with each inspection Semaan (2011). Thus, after each inspection, the CI is reevaluated for all inspected components and the updated curve should go throw the new observed point creating new Weibull deterioration curve (UDC) so, with each inspection, it becomes more and more precise.

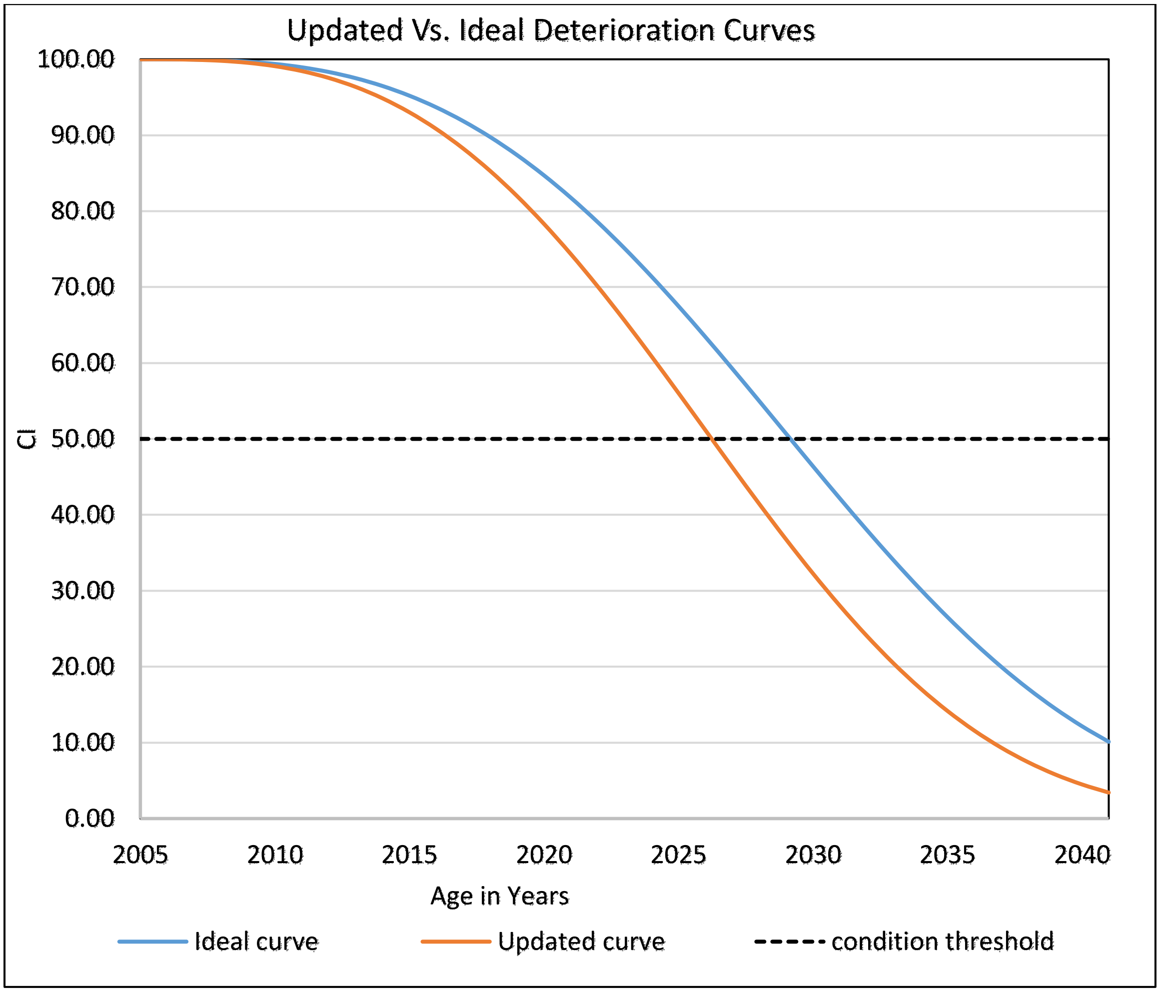


Figure 3-5 Updated vs. Ideal Deterioration Curves

At time of the inspection

$$\mathrm{CI} = 100 \times e^{\left(\frac{t1}{\tau}\right)^{\delta}}$$

$$\mathrm{mCI} = e^{\left(\frac{t1}{\tau}\right)^{\delta}}$$

$$\tau = \frac{t1}{\sqrt[\delta]{-\ln(\frac{\mathrm{CI}}{100})}}$$

$t1$: The time of the inspection

CI: after inspection

The impact of a repair option was also estimated as the difference between the before-repair condition and the estimated after-repair condition. The after-repair CI, depends on the type of repair action, for example, if the full replacement was to be chosen the condition of the system after the repair will return to its best condition. Otherwise, it can be expressed as once the decision was made to repair a certain defect its severity will become zero. Applying equation 3.6 will result in the after-repair condition.

$$After\ repair\ Sy_{CI} = \sum_i^I \left(\frac{xi \times Dwi \times Dsi}{100} \right) \qquad \text{Equation 3-6}$$

Where:

Dw: defect weight repaired

Ds: after repair defect severity

$$xi = \begin{cases} \mathbf{1} & \text{if defect } i \text{ is selected to be repaired} \\ \mathbf{0} & \text{otherwise} \end{cases}$$

The improvement of the system condition also can be calculated using equation 3.6.

$$IM = \sum_i^I \left(\frac{x_i \times Dw_i \times (Das_i - Dbs_i}{100} \right) \qquad \text{Equation 3-7}$$

Where:

Das: defect severity after repair

Dbs: before repair defect severity

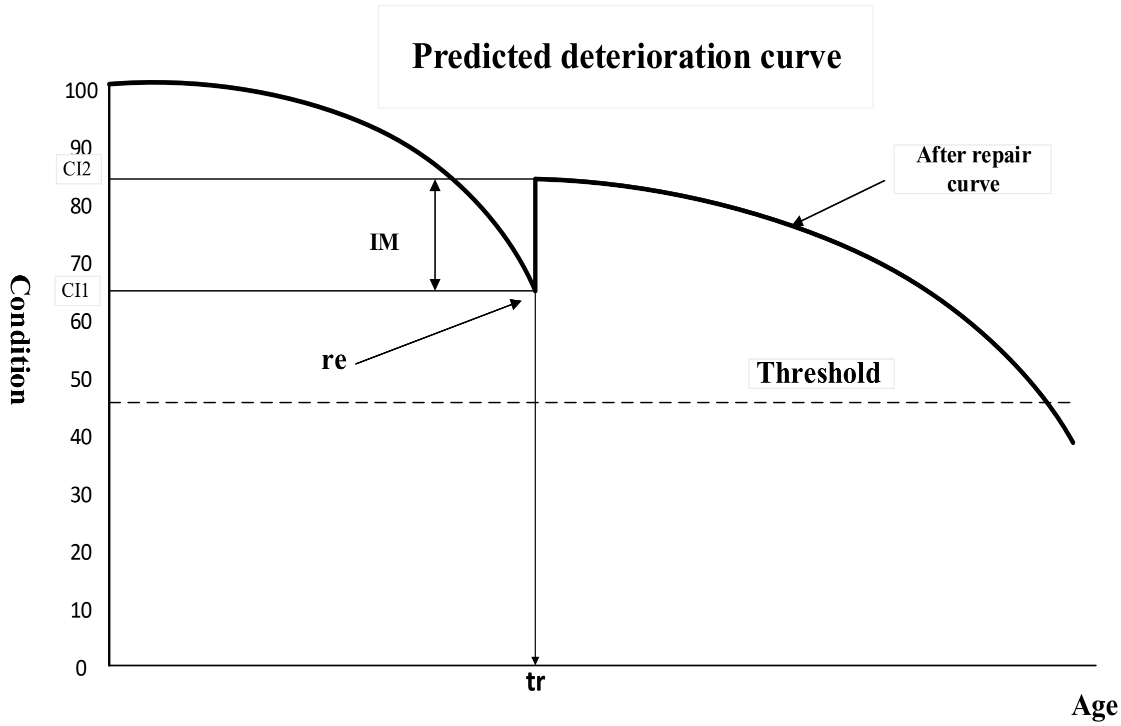


Figure 3-6 Weibull curve after maintenance

Since in each building system there could be 33 different defect which requires a lot of time and may not be also cost-effective for simplicity Eweda grouped all the defect that could occur in any system to only three types which are damage, performance, and appearance. The combination of repairing the defect will equal 2^3 repair scenarios ranging from the do nothing to full replacement. In this thesis, deterioration behavior after a repair action is assumed to follow the same pattern before the improvement based on Weibull distribution. According to Ewada (2011), the condition of building system must not be less certain values (critical threshold). These values should be entered in the optimization model as condition constraints. In this thesis, the critical threshold is assumed to be 50. The system is not allowed to reach 50 meaning that a maintenance action should be done in order to prevent the architectural system from reaching 50.

3.5 Repair Cost Model

The optimization model requires a way of estimating the cost corresponding to the maintenance action. In this thesis, we attempt to estimate the cost associated with the maintenance and replacement activities. In the proposed optimization model, the repair cost could be assumed or linked to the system condition as a percentage of the full replacement cost and the surface area of the system under consideration. However, the user has the flexibility of changing these values. Which can be represented mathematically as:

$$\mathrm{LCC} = \sum_{t=1}^{T} \sum_{i=1}^{I} CrSp_{i,t}$$

Equation 3-8

Where:

$CrSp_{i,t} = the\ maintenace\ cost\ of\ space\ i\ at\ time\ t$

$T = the\ total\ number\ of\ time\ periods$

$I = total\ number\ of\ spaces$

3.6 Multi-objective optimization

The maintenance of buildings is becoming more and more complicated. One reason is that buildings are made up of many components which may or may not depend on each other. This optimization model tries to find the best combination of maintenance decisions over the maintenance plane horizon. In this thesis, we intended to establish a plane of future maintenance and replacement actions for each architectural systems over the period [0, t]. The interval [0, t] is the maintenance plane horizon. During this period, the system is either, maintained, replaced, or no action is taken. This section illustrates in details the main features of the particle swarm optimization (PSO) that will be applied to the multi-objective optimization model. The section comprises three subsections, which are the optimization algorithm basic features, the model development. The optimization algorithm basic features tackle several topics such as the representation of the decision variables.

The final step after the condition evaluation for all building systems is the selection of repair, replace, and do-nothing options, and analysis of the associated costs for all nominated building component in need of treatment. The maintenance and rehabilitation analysis procedure depend on the following data and decision criteria: space type, space area, space condition, systems inside the spaces condition, current condition assessment, defect severity, defect type, minimum acceptable service or condition level, maintenance cost, budget constraint, and analysis period.

3.6.1 Particle swarm optimization

3.6.1.1 Objective function

Most researchers propose a set of objectives for maintenance and rehabilitation plans include: to minimize the present worth of overall treatment costs over the analysis period and to keep the building condition over the minimum acceptable level with the Budget and resources available. Generally, there is an inverse relationship between the cost of maintenance and condition of a building; since, whenever the condition of a building is increased, the cost of the maintenance will increase considerably. Hence, finding a proper decent trade-off between these two-objective functions has become a crucial issue for the facility managers (Feng et al., 2000). These objectives could be combined by allocating a proper weighting factor to each (Fwa et al., 1996). Furthermore, in building maintenance and rehabilitation management, the selection of best maintenance alternatives for a large number of components over multiple time periods under constraints and restrictions is a challenging issue. Thus, it is important to optimize the M&R decision considering multiple objectives such as minimum cost and maximum condition, etc. Therefore, the multi-objective optimization of activities is developed using the particle swarm optimization technique.

The multi-objective optimization can be presented mathematically as the following:

a) Minimize the total maintenance cost:

$$\mathrm{LCC} = \sum_{t=1}^{T}\sum_{i=1}^{I} CrSp_{i,t}$$

Equation 3-9

Where:

$CrSp_{i,t} = the\ maintenace\ cost\ of\ space\ i\ at\ time\ t$

$$CrSp_{i,t} = \sum_{j=1}^{J}\sum_{m=1}^{M} x_{m,j,i,t}\ CSy_{j,m,t}$$

$$x_{m,j,i,t} = \begin{bmatrix} 1\ if\ maintenace\ action\ m\ applied\ to\ system\ j\ on\ space\ i\ at\ time\ t \\ 0 \hfill otherwise \end{bmatrix}$$

$CSy_{j,m,t} = cost\ of\ repearing\ system\ j$ for maintenace action m $at\ time\ t$

b) Maximize Building condition

$$BCI = (\sum_{t=1}^{T}\sum_{i=1}^{I} Spw_i\ \ Spc_{i,t})/T$$

Equation 3-9

Where:

$BCI = Building\ condition$

$Spw_i = space\ \ i\ \ weight$

$Spc_{i,t} = space\ i\ condition\ at\ time\ t$

$T = the\ total\ number\ of\ time\ periods$

$$Spc_{i,t} = \sum_{j=1}^{J}\sum_{m=1}^{M} Syw_j\ \ (Syc_{j,t}\ - x_{m,j,i\ ,t}\, Syc_{j,m,t}\,)$$

$$x_{m,j,i\ ,t}\ = \begin{bmatrix} 1\ if\ maintenace\ action\ m\ applied\ to\ system\ j\ on\ space\ i\ at\ time\ t \\ 0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad otherwise \end{bmatrix}$$

$Syw_j = system\ j\ weight$

$Syc_{j,t} = system\ j\ conditon\ \ at\ time\ t$

$Syc_{j,m,t} = system\ j\ conditon$ for maintenace action m $at\ time\ t$

$J = total\ number\ of\ systems\ inside\ space\ i$

$M = total\ number\ of\ maintenace\ action$

$I = total\ number\ of\ spaces$

3.6.1.2 Decision Variables

Discretized value is the decision that the optimization model should choose which is identified and coded as shown in table 3.1. Where Performance is represented as d1, Appearance d2, and Damage d3. If the optimization model selects the code 0 (the do nothing option) the associated cost will be zero but the system will continue to deteriorate. Differently, if code 8 (full replacement) was chosen the condition of the system will return to its perfect condition. Otherwise, if the code from 1 to 7 were preferred the repair option ranging from repairing d1 to repairing all the defects d1+d2+d3 as shown in table 3.1.

Table 3-1 maintenance and repair Codes

Code	Description
0	do nothing
1	repair d1
2	repair d2

3	repair d3
4	repair d1+d2
5	repair d1+d3
6	repair d2+d3
7	repair d1+d2+d3
8	Full replacement

3.6.1.3 Particle swarm particle representation

There is no previous work found in the literature addressing PSO particle representation for the building maintenance optimization. A Compatibility between problem solution and the particle through a correct representation of particle positions is one of the essential procedure in a functional particle swarm optimization algorithm. In most optimization problems, the variables take two forms, either to be discreet or continuance , the difference between these two types of variables is in two ways, for discrete the velocity must be transformed to probability change that is chance for the binary take the value of 1, and the practical coordinate is composed of binary values. PSO was originally designed for qualitative variables.

As noted before each particle should represent a solution to the optimization problem. For each particle an I×T matrix is generated where I is the total number of systems and T is the total number of the years (planning horizon). Every element of the matrix is a random number chosen from the set {0, 1, 2…M}, where M is the total number of maintenance actions. Moreover, in each row of the matrix the value of all of the elements is 0; except one element, which represent a decision variable as discussed on sub-section 3.6.1.3. The optimization should be able to find the best time to apply the maintenance action and the best decision. Each repair option has its own effect on condition and repair cost. Each particle is a view of what future might be, it represents a repair scenario. The structure of a particle encoding is shown in table 3.2.

Table 3-2 Direct representation.

Particle i

	y1	y2	y3	y4	y5
Building system 1	0	0	6	0	0
Building system 2	0	4	0	0	0
Building system 3	0	0	0	0	8
Building system 4	0	7	0	0	0
. . .	. . .	. . .	. . .	. . .	. . .
Building system I	5	0	0	0	0

To improve the search efficiency and for the sake of simplicity, it is recommended to propose an indirect Particle Swarm Optimization (PSO)-based approach (da Silva 2016).Thus a combination of direct and indirect representation is proposed in this research .In indirect encoding, solutions for each particle are encoded in a position matrix, i×d. In the position matrix, the values of the matrix elements for each particle are binary values, 0 or 1. Moreover, in each row the value of all of the elements is 0; only one element, corresponding to the maintenance action, is 1.the indirect encoding is shown in table3-3:

Table 3-3 Indirect particle representation

Particle K (i×d)

	YEAR 1									YEAR N							
system 1	1	0	0	0	0	0	0	0	…….	0	0	0	0	0	0	0	0
system 2	0	0	1	0	0	0	0	0	…….	0	0	1	0	0	0	0	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
system i	0	0	0	0	0	0	0	0	…….	0	0	0	0	0	0	0	0
	d1	d2	d3	d1+d2	d1+d3	d2+d3	d1+d2+d3	replacement	…….	d1	d2	d3	d1+d2	d1+d3	d2+d3	d1+d2+d3	replacement

3.6.1.4 Updating local best position

Based on the zero initialization and the indirect representation the initialization of all the elements in the particles' matrix $K(k \times j)$ are generated to be zero, thus the personal best position and the initial position of each particle are equal. $Pbesti, n(0) = Xi, n(0)$, where $Xi, n(0)$ is the initial position of the nth dimension of the ith particle and in the swarm $Xi, n(0)$ is the initial position of the nth dimension of the ith particle and in the swarm. This also applies for initial velocity $vi, n(0) = 0$, for all $i = 1, \dots \dots .., n$, where n is the number of particles. The best position for particle i, $Pbesti\ (z)$ is referred to the best position the particle arrives at up to date. Whiten each iteration the update of the $Pbest$ will happened only if a better fitness than that of current $Pbest$ position. Mathematically it can represented according to equation 3.12 as shown below (Zhang et al., 2012).

$$pbesti(z+1) = \begin{cases} pbest(z) & if\ F\big(pbest(z)\big) < F\ \big(xi(z+1)\big) \\ xi(z+1) & otherwise \end{cases}$$

Equation 3-10

Where i = 1, 2, …, I, and I is the total number of particles in the swarm (i.e. the swarm's size)

3.6.1.5 Updating the Global Best Positions

The most important part of PSO optimization is the identifying of the best particle $Gbest$ (z) among the swarm because this particular particle will act as a leader and lead other particles to its position as well as it is the best solution reached by the swarm at the current iteration. It is obvious and straightforward mater in single objective problem to find the global leader.

For the multi-objective optimization problem .In this dissertation the, sigma method will be used which was developed by Mostaghim and Teich, 2003 due to its simplicity. An amount σi for each particle is calculated based on equation 3.13

$$\sigma = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2}$$

Equation 3-11

Then the σi values which belong to the leader particles are separated from the other. After that the difference between the non-dominate solution σg and each particle sigma value σi are assigned to each particle. Next, particle g that has the lowest difference value to particle i is chosen as the global leader particle. Therefore, each solution which has a closer sigma value to the sigma value of a non-dominated solution must choose that non-dominated solution as a leader solution. As shown in the figure 3.7.

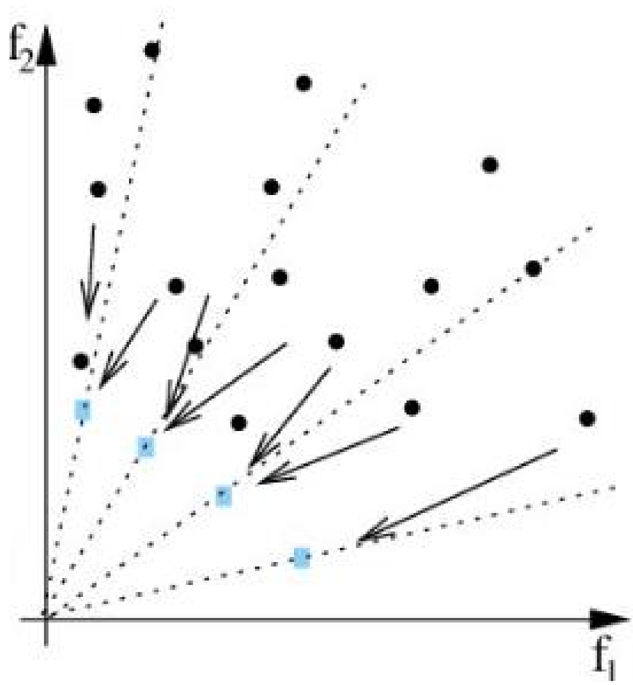

Figure 3-7 Global leader Sigma Method

3.6.1.6 Updating the Particle Velocities and Positions

For each string in the particle i matrix, all of the element are zero except the proposed maintenance action by the algorithm which will be equal to 1. For this type of discrete binary problem Maher (2015) proposed an update of velocity and position based on equations:

$$V_{i,j}(z+1) = \begin{cases} N\left(\frac{pbest_{i,j}(z)+Gbest(z)}{2}, \left|pbest_{i,j}(z) - Gbest(z)\right| - X_{i,j}, \right. & if\ U(0,1) < 0.5 \\ Gbest(z) - X_{i,j}(z), & otherwise \end{cases}$$

Equation 3-12

$$X_{i,j}(z+1) = \begin{cases} 1 & if\ (V_{i,j}(z+1) = max\{V_{i,j}(z+1)\} \\ 0 & otherwise \end{cases}$$

Equation 3-13

Chapter 4: Case Study

The Engineering, Computer Science and Visual Arts Integrated Complex (EV Complex) opened in September 2005. Located in Montreal, Canada and part of Concordia University's campus, this building was selected as a case study of an educational building to be optimized and assessed using the proposed optimization model. The objective is to use the model to help in terms of maintenance and rehabilitation actions. The EV Complex is a 17-storey, two-tower (linked on every floor) building that hosts research and graduate teaching labs, administrative offices, various studios, an art gallery, specialized amphitheaters, and two Dean's Offices, as well as other unique facilities. The third floor of both towers has been selected for this research case study as it hosts different space types and is a good example for the proof of concept.

4.1 Spaces weights

Educational buildings normally include several linked varied functional spaces (e.g., classrooms, offices, and labs), which contain diverse physical systems. Satisfactory performance of these systems directly impacts both students and faculty staff in many ways. An appropriate physical assessment of an educational building will result in satisfying a maintenance plan which will support educational process and will create a beneficial work environment. Therefore, a step by step assessment of its spaces, space areas, space types, and systems was implemented to establish an effectively optimized maintenance plan. Two-dimensional drawings saved in Adobe Acrobat© format (pdf) of the architectural plan of the building were provided by Concordia University. The first step was to analyze the space types and the area of the spaces inside the third floor of the Concordia EV building to come up with the building assets' hierarchy scheme. A list of spaces can be shown in Table 4.1. A list of the systems inside these spaces arranged according to their weight can be shown in Figure 4.5.

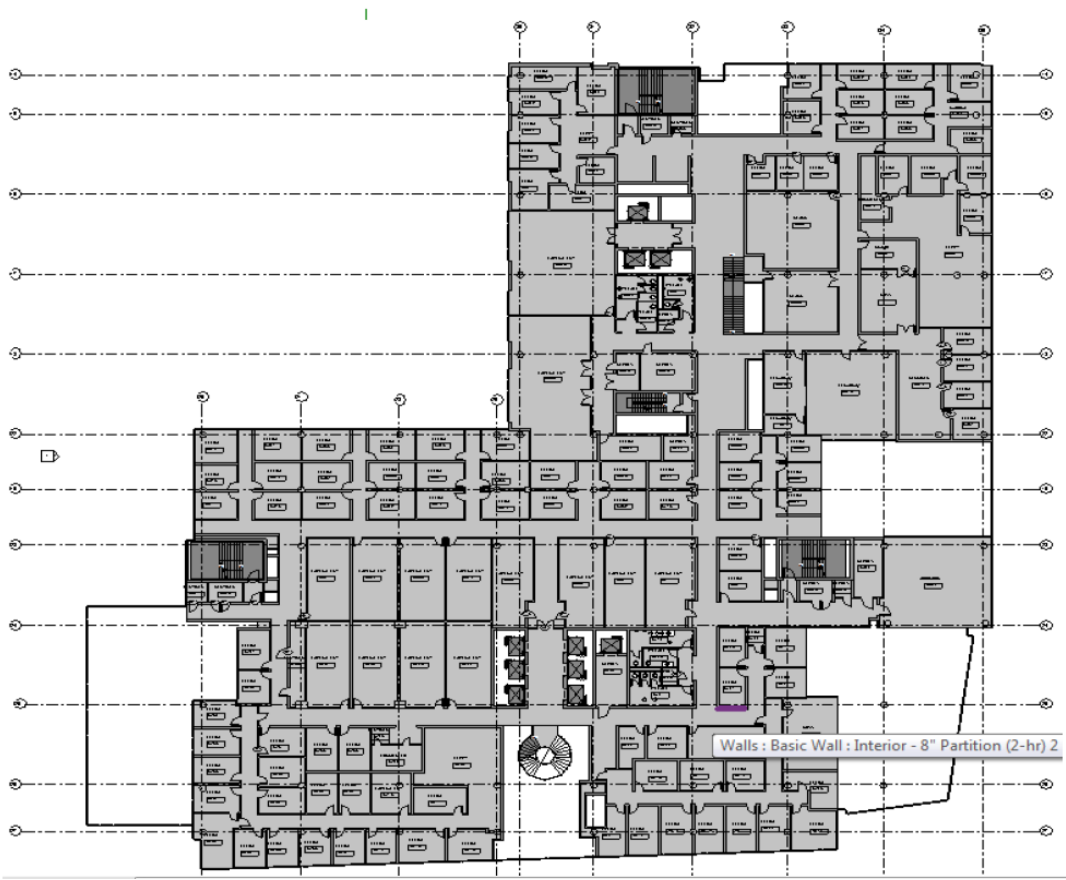

Figure 4-1 the 3rd floor of the Integrated Engineering, Computer Science and Visual Arts Complex

The ranking of spaces inside the building was done through Revit software. Schedules in Revit are a way to bring all of the information that is within the Revit software database into one place. In this case, the information available from the spaces and data collected on them was put into schedule form. Schedules are created from the view tab whiten Revit software. The Revit software allows for easy updating if any changes happen to the model;

changing the property of any space inside the model whether the space type or space area has an impact throughout the model. The benefit of Revit is that it is able to locate and update the modification automatically. Figure 4.4 shows the schedules created by Revit. Furthermore, Revit can easily calculate and detect the area of each space type and total space type area which can be helpful for the proposed optimization model.

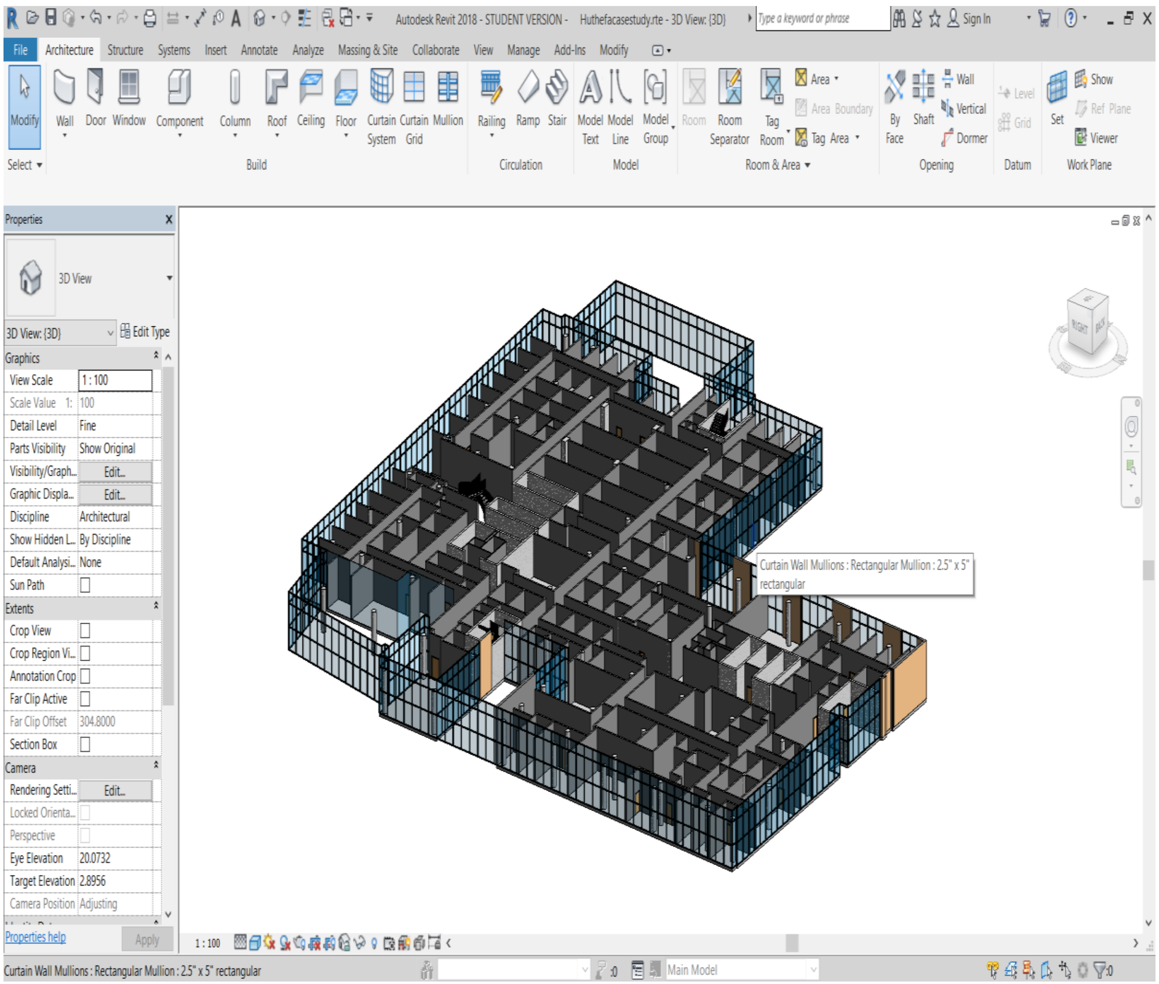

Figure 4-2 Revit model for the EV Building

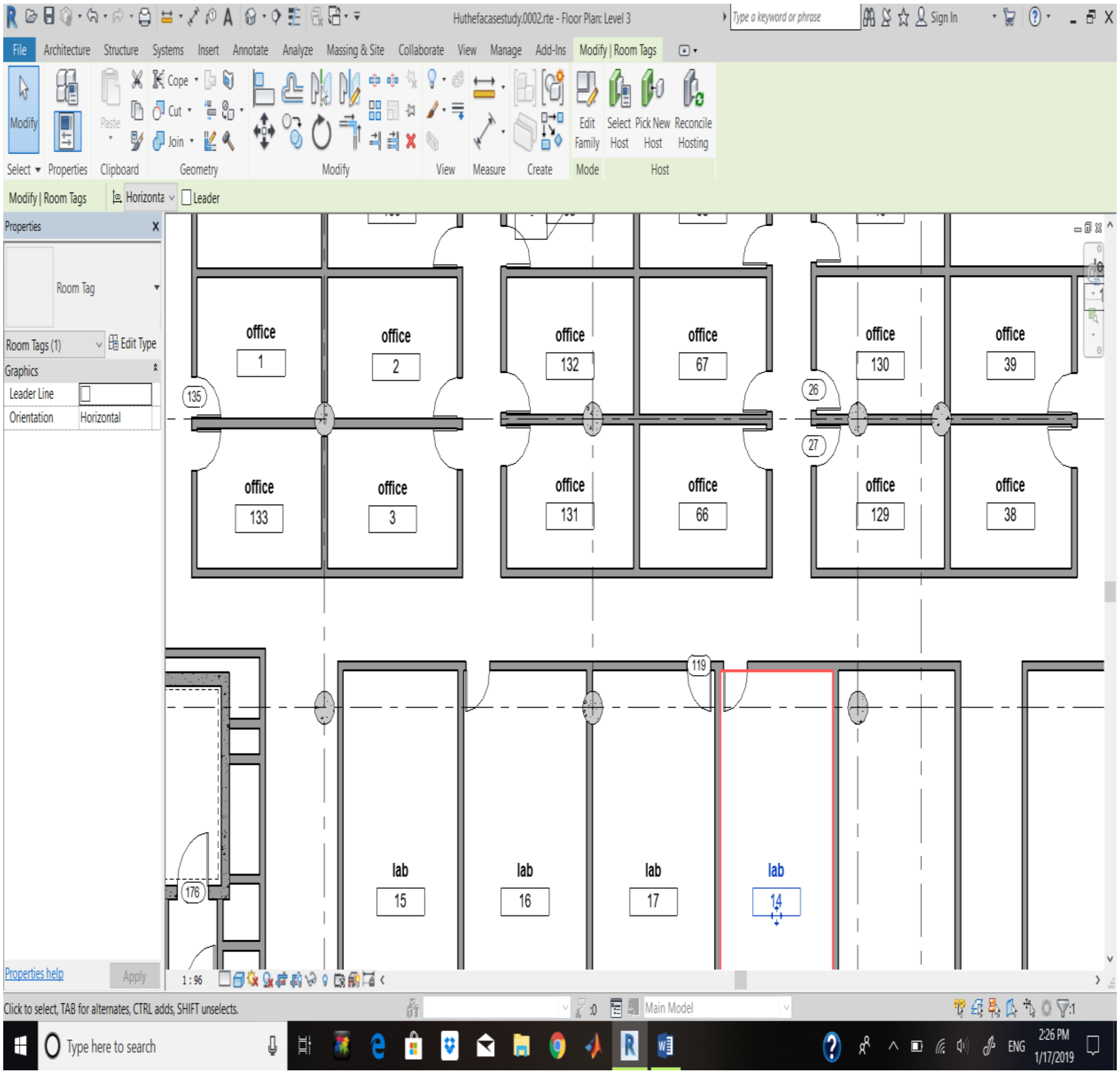

Figure 4-3 Revit model for the Case Study

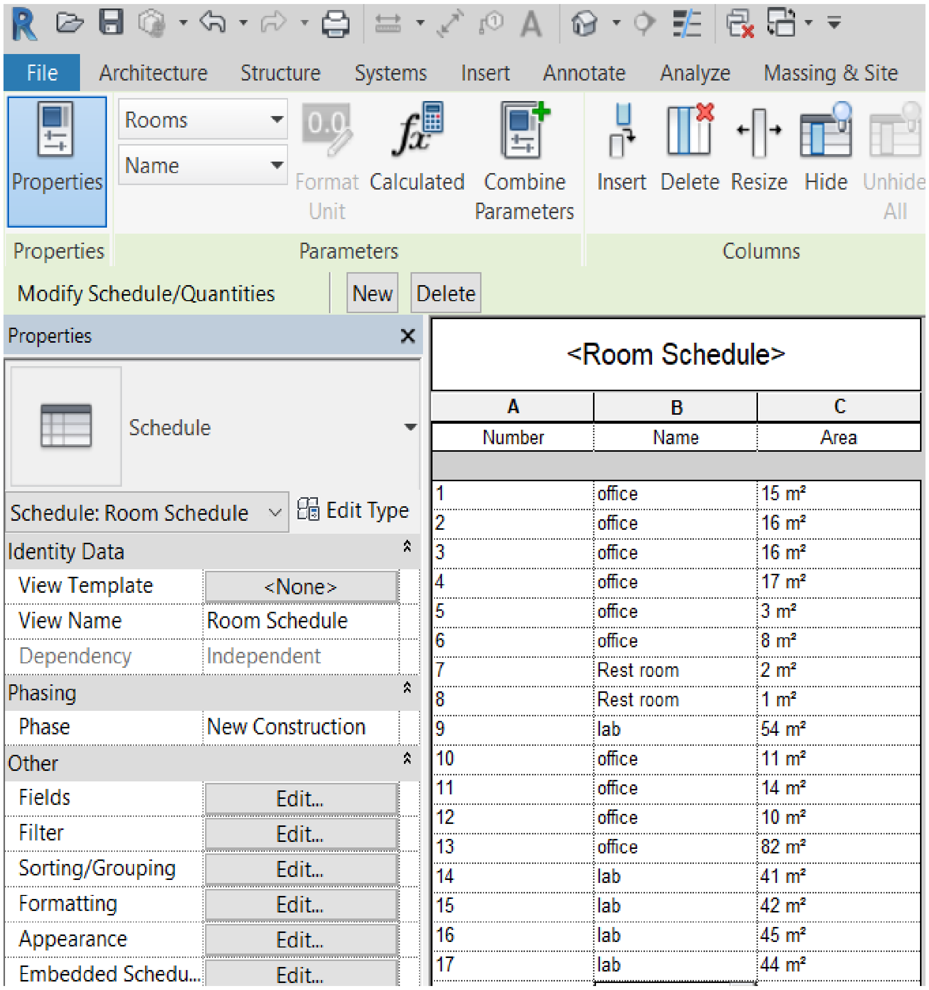

Figure 4-4 Revit seclude

Table 4-1 Spaces types and total Area

Space type	Number of space	Total floor Area (sq.mt)
Classroom	5	500
Office	102	1050
Laboratories	17	2000
Restrooms	6	150
Lunch room	2	280
Lobby/Corridors	1	1000
Auditoriums	1	120
Total Area	5100 sq.mt	

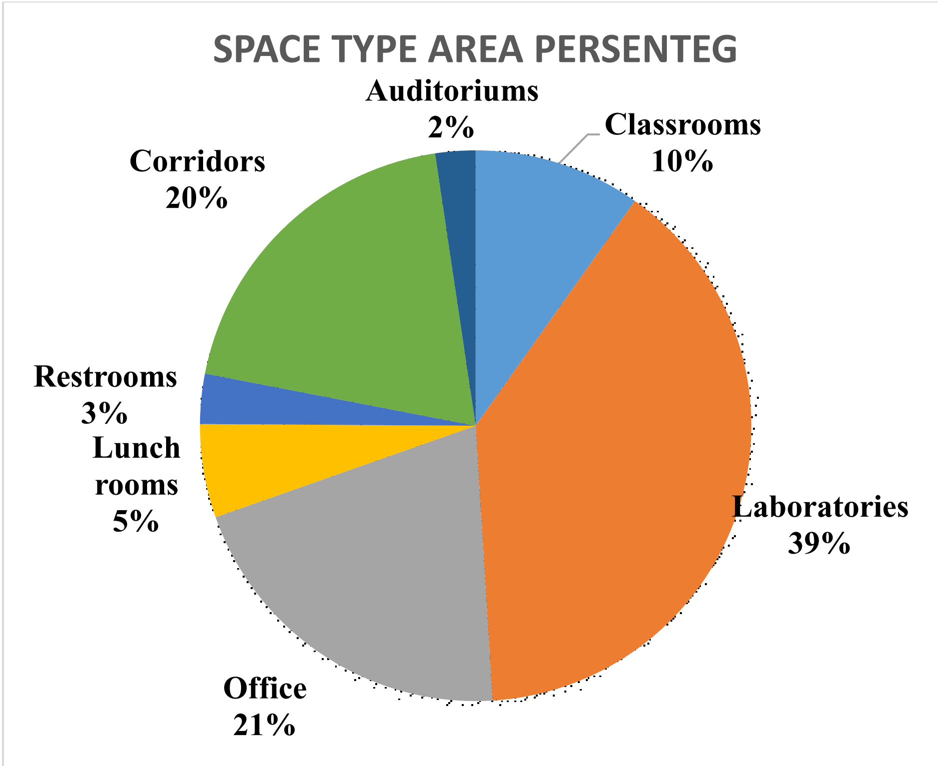

Figure 4-5 Area Spaces types Percentage

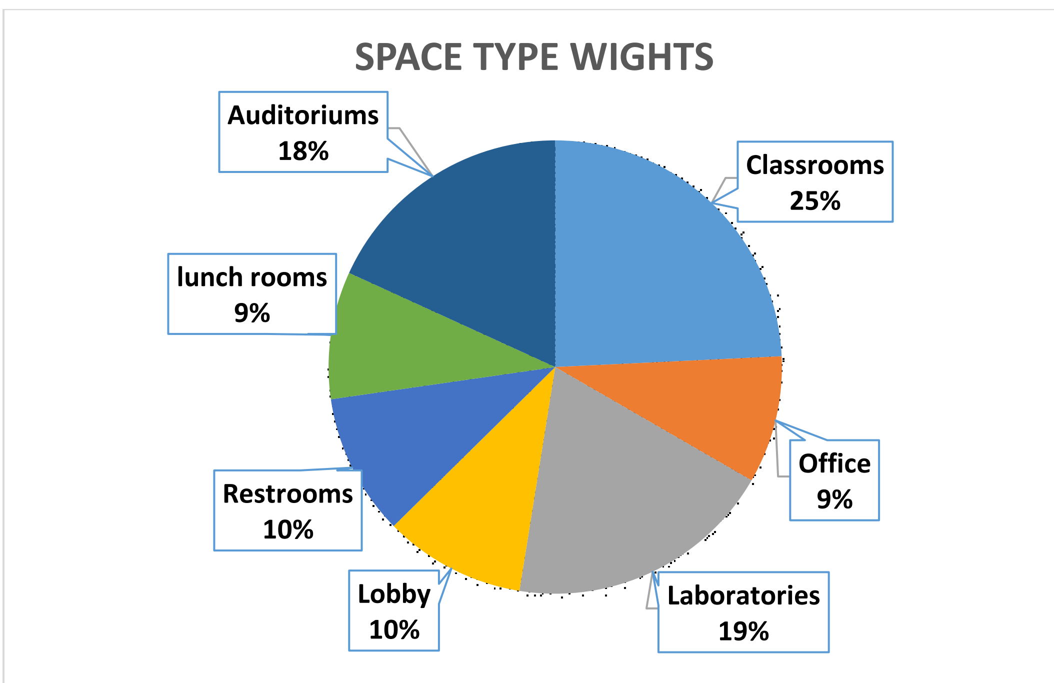

Figure 4-6 Space Type Weight (Ewada 2014)

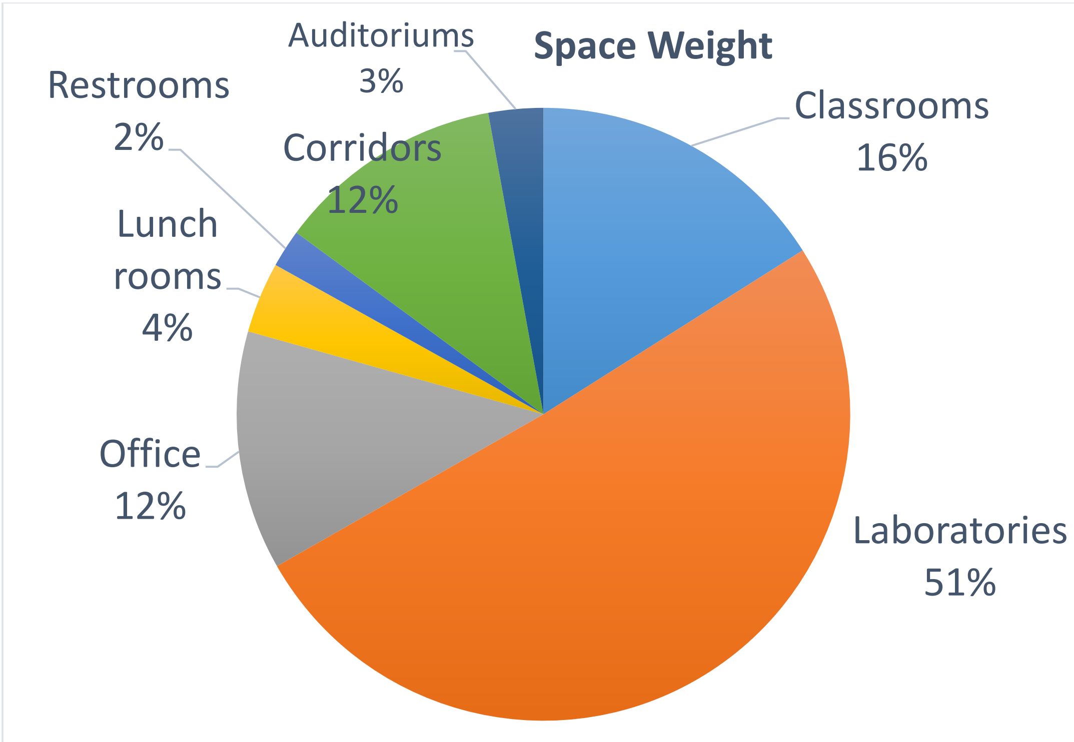

Figure 4-7 case study Spaces Type weights

Table 4-2 Space types weights

Space type	Space Weight (QS)	Total Space Type Area	Space type Area percentage	Space Weight(QS)*Space type Area percentage	Space Type Weight	Space weight /m2
Classrooms	0.24	500	0.0980392	0.023529412	16.019	0.0003203
Laboratories	0.19	2000	0.3921568	0.074509804	50.727	0.0002536
Office	0.09	1050	0.2058823	0.018529412	12.615	0.0001201
Lunch rooms	0.1	280	0.0549019	0.005490196	3.7378	0.0001334
Restrooms	0.1	150	0.0294117	0.002941176	2.0024	0.0001334
Corridors	0.09	1000	0.1960784	0.017647059	12.014	0.0001201
Auditoriums	0.18	120	0.0235294	0.004235294	2.8834	0.0002402
TOTAL	1	5100	1	0.146882353	100	

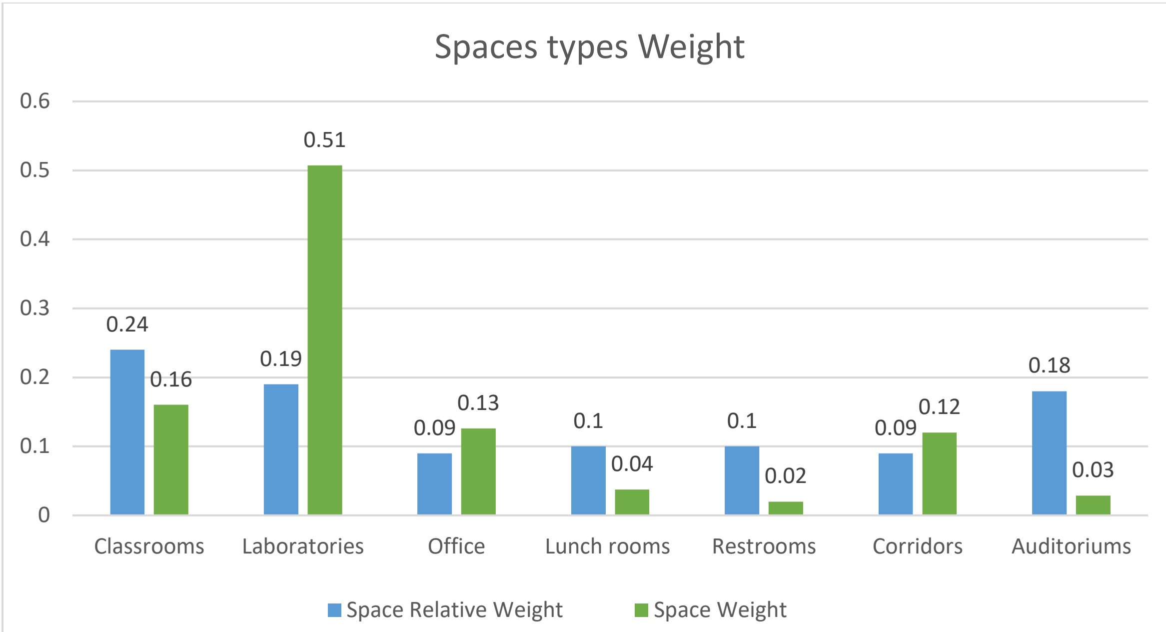

Figure 4-8 Spaces type weights Ewada (2014)

The weight of the system inside each space type is adapted from (Ewada 2014). The comparison is shown in figure 4.9. Based on the figure the windows and floor system type have the highest weight while door system type has the lowest

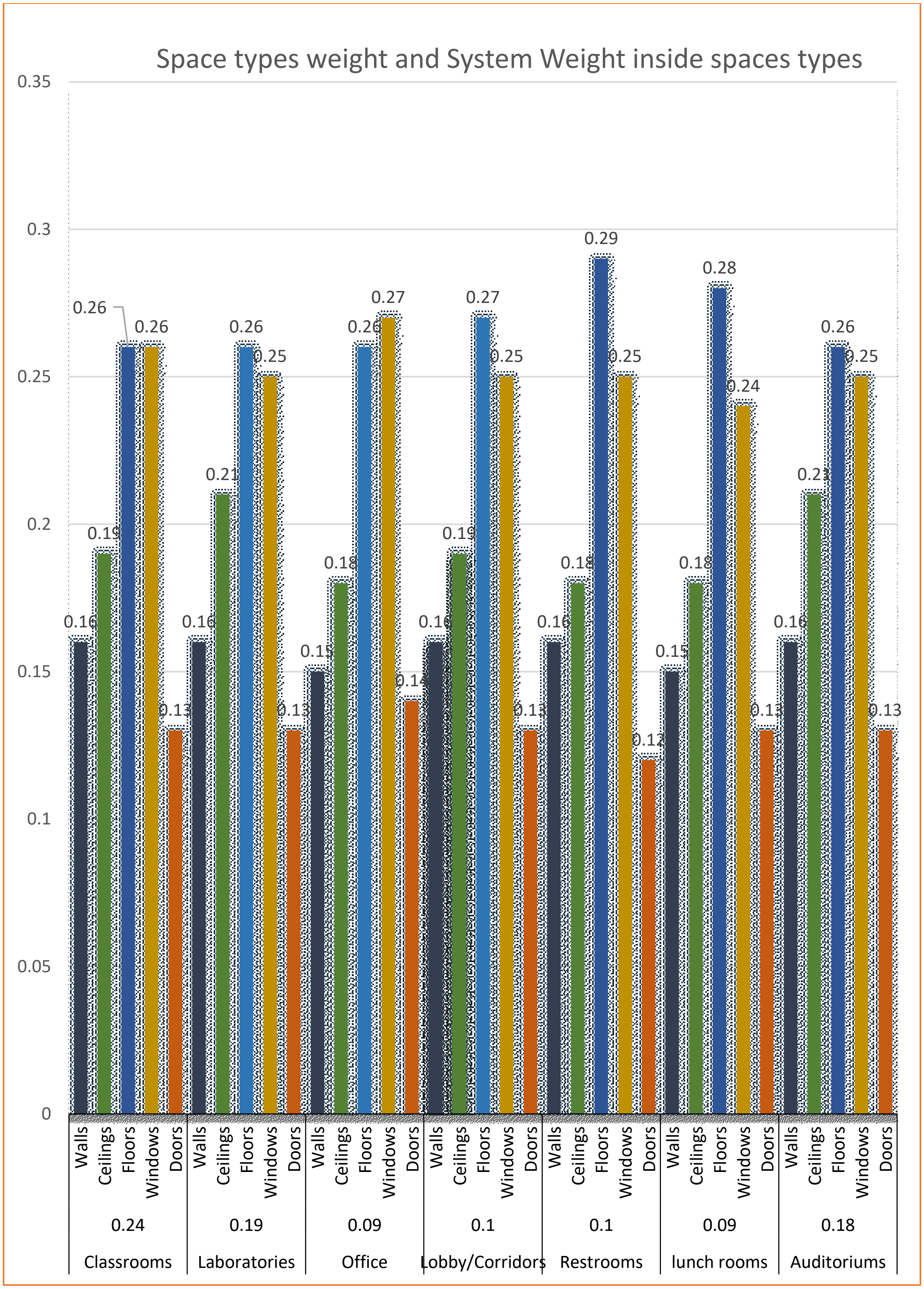

Figure 4-9 Spaces types weight and System Weight inside space type (Ewada2014)

Based on Ewada's (2014) study of the EV building, Figure 4.10 illustrates a comparison of the type of defect and their weights different according to system type. According to the figure, damage type defects in floors had the highest weight at 54%, while the appearance defect type in walls was also at 54%. For doors and windows, the performance and damage defect was equally important since they had the same weight and this was expected given that they both function to protect the building from outer climate. The case is different for ceilings because damage and appearance have the same weight. Overall, it was observed that the appearance of architectural systems is of the highest weight due to the fact that architectural systems are mainly used as the final finish and cover building systems such as pipes, cables, and other structural components and systems.

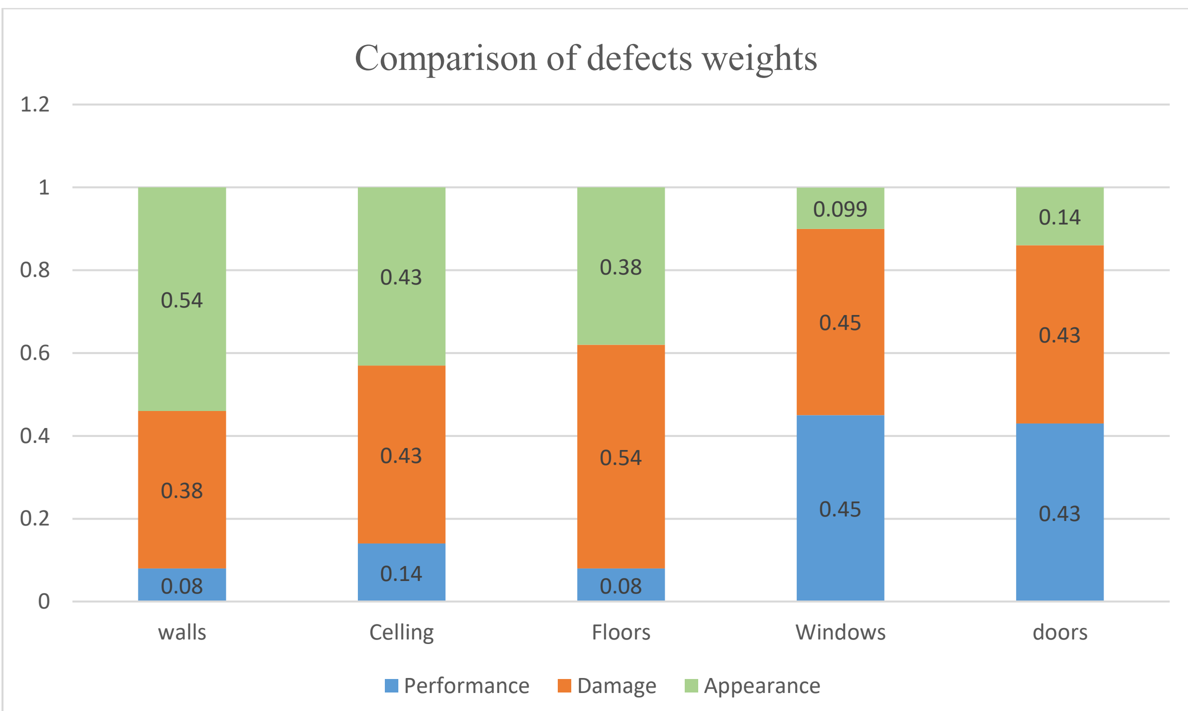

Figure 4-10 Defect type weights for each System (Ewada 2014)

4.2 Weibull deterioration curves

After finishing the space assessment, the second model which is based on the Weibull function was initiated. In this model, deterioration curves are purposed for prediction of future condition of architectural systems inside different spaces. Figure 4.11 describes the deterioration curve of the door system. Here, only two pieces of information are required: the age and the service life. The age of an asset is the most important factor since it is a good indication of the overall degradation process. Age is easily calculated and communicated to decision makers, making it a popular metric to look at for decisions. In addition, Weibull is very beneficial since the input processes as well as calculations process are significantly faster, easier, and more uncomplicated. The only limitation to this method is that age is not the only factor that contributes to the deterioration of a building system, this includes other factors such as usage, maintenance levels, etc. The EV building opened in 2005, so it is assumed that all of the conditions of the architectural system were at their best in 2005. According to the graph, doors are in good condition at present time but are deteriorating with a progressive rhythm. In year 2029, the condition of the doors will be at 50%. Thus, it is compulsory that maintenance or replacement action be considered. Similar graphs were constructed for other systems and can be found in the Appendix D.

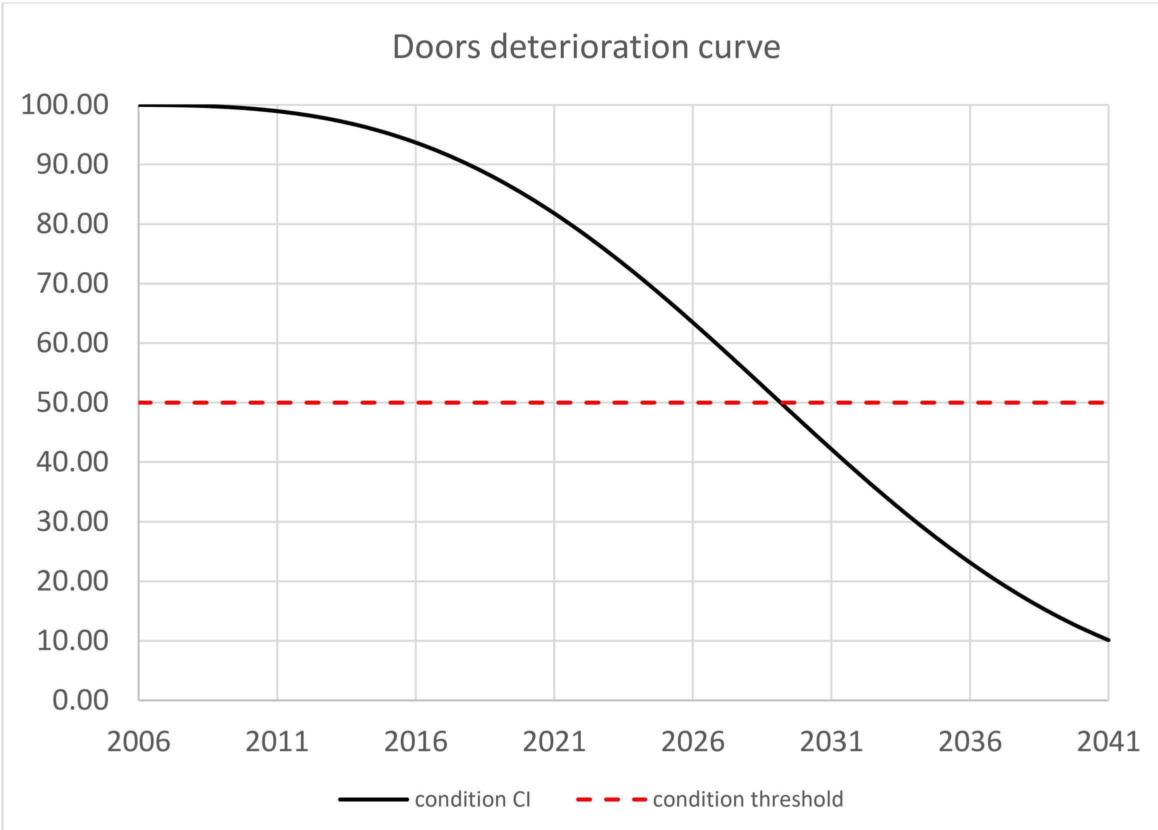

Figure 4-11 Doors deterioration curve

Ceilings, doors, windows and floors deterioration curves are illustrated in Appendix

4.3 Multi-Objective Particle swarm optimization

A fundamental part of facility management is the recognition of what maintenance activity to perform against the system inside the building at a specific point in time while taking all kinds of constraints into account. Overall analysis should consider current and future condition states, in addition to the costs required to maintain and repair or replace building systems. The objectives of optimization are to minimize the total cumulative net present value LCC over the analysis period and minimize the space-based condition, given constraints on CI and Cost by adjusting the decision variable in the Maintenance Action rows.

Multi-objective particle swarm optimization was implemented to optimize the building's maintenance and repair actions over an analysis period. The results show that this algorithm can find an optimal maintenance and repair action plan. This optimization problem is the selection of the optimal treatment action from eight maintenance actions for each system inside each space at the Concordia EV building over five years in order to implement the MOPSO algorithm. The parameters of the problem are a swarm size of 100 and the number of iterations is 100.

The MOPSO optimization framework was implemented by generating code in MATLAB. After 100 generations, thirteen non-dominated solutions were found, as shown in Figure 4.15. The first objective function was to maximize the average condition of Building for the study period (in this research, five years) and the second was to minimize the cost. When the first iteration random number was generated, these random number were then exported as an input to an Excel file to be read for the proposed random number so as to generate the condition state and cost that will be associated with the proposed random number. Afterward, the global leader particles were chosen via Sigma method to determine the leader particle for each particle based on the global leader position, particle position, particle velocity, and distance and the particle updates its position and so on until it reaches the best position proposed by the algorithm. The cost function code can be found in Figure 4.12, the condition function code in Figure 4.13, the Sigma method for the leader particle in Figure 4.14, and the rest of the code can be found in the Appendix section. The pareto results would be in figure 4.15.

swarm1.m × costHuthaifa.m × transferxtoy.m × +

```
% objective function-minimisation of treatment cost
 function total_cost = costHuthaifa(x)
disc_rate = 0;
maint_cost=xlsread('cost1');
par_dim=4422;
No=6;
total_cost = 0;
year=0;
for j=1:No
    for k=1:par_dim
        total_cost = total_cost + maint_cost(k,j)*x(k,j,:);
    end
    m = mod(25,5);
    if m == 0
        year=year+1;
        total_cost = total_cost*(1+disc_rate)^(-1*year);
    end
end
 end
```

Figure 4-12 Matlab cost function

```
x=y;
par_dim=4422;
No=6;
CI_max=100;
maxseverity=100;
condition_index = 0;
CI = zeros(par_dim,No);
repearingweight= xlsread('repearingweight');
severity= xlsread('severity1');
for j=1:No
    for k=1:par_dim
        if x(k,j)==1
            CI(k,j)=repearingweight(k,1)*severity(k,j);
        else
            CI(k,j)=0;
        end
        condition_index = condition_index + CI(k,j);

    end
end
condition_index = condition_index /5;
end
```

Figure 4-13 condition function Matlab code

```
minA_cur2=min(A_cur(:,2));
m1A_cur=zeros(m,1);
m2A_cur=zeros(m,1);
for f=1:n
    m1D(f)=(D(f,1)-minA_cur1)/(maxA_cur1-minA_cur1);
end
for f=1:n
    m2D(f)=(D(f,2)-minA_cur2)/(maxA_cur2-minA_cur2);
end
for f=1:n
    sig_A(f)=((m1D(f)^2)-(m2D(f)^2))/((m1D(f)^2)+(m2D(f)^2));
end
for i=1:(size(A_cur,1))
    m1A_cur(i)=(A_cur(i,1)-minA_cur1)/(maxA_cur1-minA_cur1);
end
for i=1:(size(A_cur,1))
    m2A_cur(i)=(A_cur(i,2)-minA_cur2)/(maxA_cur2-minA_cur2);
end
for i=1:(size(A_cur,1))
    sig_S(i)=((m1A_cur(i)^2)-(m2A_cur(i)^2))/((m1A_cur(i)^2)+(m2A_cur(i)^2));
end
sig_S=sig_S';
sig_A=sig_A';
distHu=zeros(m,n);
for i=1:m
    for j=1:n
        distHu(i,j)=sig_S(i)-sig_A(j);
    end
end
distHu=abs(distHu);
[gh,hg] = min(distHu');
gh = gh';
hg = hg';
NewCol=[];
for i=1:m
NewCol=[NewCol;i];
```

Figure 4-14 Matlab code sigma method

Figure 4.15 below represent the Pareto results. The red points are the best solutions or the global leader particles. Table 4.3 below is a snapshot of the maintenance plan. The full maintenance plan can be found in Appendix F.

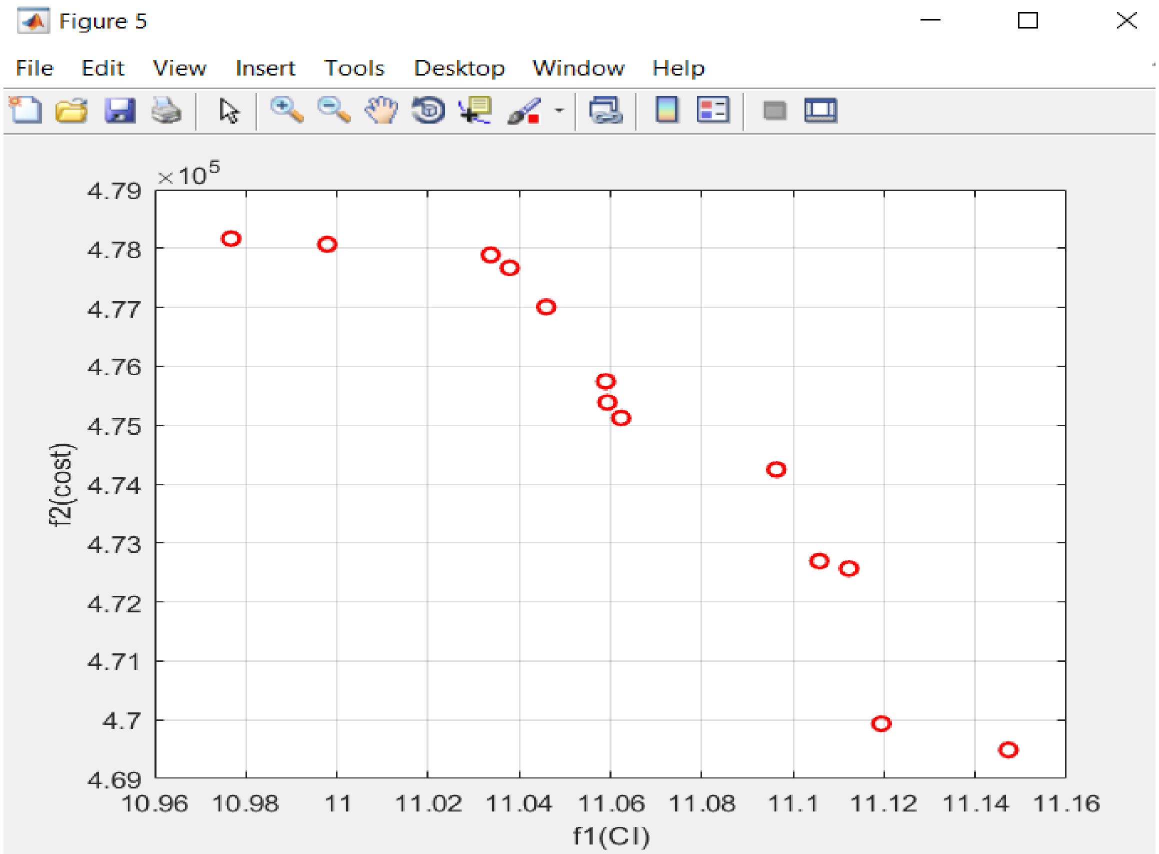

Figure 4-15 maintenance plane Pareto frontier

Table 4-3 A snapshot of the maintenance plan

Floor	Space ID	Space type	Space type WEIGHT	SPACE AREA / m2	System	System Weight	Maintenance plane				
							Year 1	Year 2	Year 3	Year 4	Year 5
3	**1**	Classroom	24	95	Walls	0.16	0	1	0	0	0
					Ceilings	0.19	0	0	0	3	0
					Floors	0.26	0	0	1	0	0
					Windows	0.26	0	0	0	0	0
					Doors	0.13	0	0	0	0	0
3	**2**	Classroom	24	98	Walls	0.16	5	0	0	0	0
					Ceilings	0.19	4	0	0	0	0
					Floors	0.26	2	0	0	0	0
					Windows	0.26	0	0	0	0	0
					Doors	0.13	0	1	0	0	0
3	**3**	Classroom	24	98	Walls	0.16	0	0	0	0	0
					Ceilings	0.19	0	1	0	0	0
					Floors	0.26	0	0	4	0	0
					Windows	0.26	0	0	0	0	0
					Doors	0.13	0	1	0	0	0
3	**4**	Classroom	24	98	Walls	0.16	5	0	0	0	0
					Ceilings	0.19	4	0	0	0	0
					Floors	0.26	2	0	0	0	0
					Windows	0.26	0	0	0	0	0
					Doors	0.13	0	1	0	0	0
3	**5**	Classroom	24	98	Walls	0.16	0	0	0	0	0
					Ceilings	0.19	4	0	0	0	0
					Floors	0.26	2	0	0	0	0
					Windows	0.26	0	0	0	0	0
					Doors	0.13	0	1	0	0	0
3	**5**	Office	0.09	8	Walls	0.16	5	0	0	0	0
					Ceilings	0.19	4	0	0	0	0
					Floors	0.26	2	0	0	0	0
					Windows	0.26	0	0	0	0	0
					Doors	0.13	0	1	0	0	0
3	**5**	Office	0.09	11	Walls	0.16	5	0	0	0	0
					Ceilings	0.19	4	0	0	0	0
					Floors	0.26	2	0	0	0	0
					Windows	0.26	0	0	0	0	0
					Doors	0.13	0	1	0	0	0
3	**5**	Office	0.09	10	Walls	0.16	0	7	0	0	0
					Ceilings	0.19	5	0	0	0	0
					Floors	0.26	0	6	0	0	0
					Windows	0.26	0	0	0	0	0
					Doors	0.13	4	0	0	0	0
3	**5**	Office	0.09	9	Walls	0.16	0	0	0	0	0
					Ceilings	0.19	1	0	0	0	0
					Floors	0.26	1	0	0	0	0
					Windows	0.26	0	3	0	0	0
					Doors	0.13	0	3	0	0	0
3	**5**	Office	0.09	15	Walls	0.16	0	0	0	0	0
					Ceilings	0.19	1	0	0	0	0
					Floors	0.26	1	0	0	0	0
					Windows	0.26	3	0	0	0	0
					Doors	0.13	3	0	0	0	0

4.4 Summary

In this chapter, the proposed methodology was implemented. At first, the relative importance weights of the spaces and the different systems inside each different space of the EV building were defined along with the weights of defects. The case study continued with the condition prediction model. Systems deterioration curves were constructed and based on the results, future conditions was determined. The final stage of the process was the implementation of the optimization model which used particle swarm to generate various combinations of properly maintenance actions to obtain the best results (minimum cost and condition). Finally, the zero particle initialization stage, updating local position and global leaders, and velocity were described in detail.

Chapter 5: Results and analysis

5.1 Space ranking

Figure 5.1 shows Ewada's (2014) questionnaire results which were conducted on educational buildings. Based on his study, the classroom space types appear to have the highest weight as compared to other space types. These findings seem correct given that most educational activity happens in these space types. Moreover, the number of users that use classrooms are more in compression with other types. The office space type shows be the lowest and the reason for this is that office space types are only occupied by teachers. Usually, the student-teacher ratio (the number of students who attend a school or university divided by the number of teachers in the institution) is much higher than the teacher-student ratio.

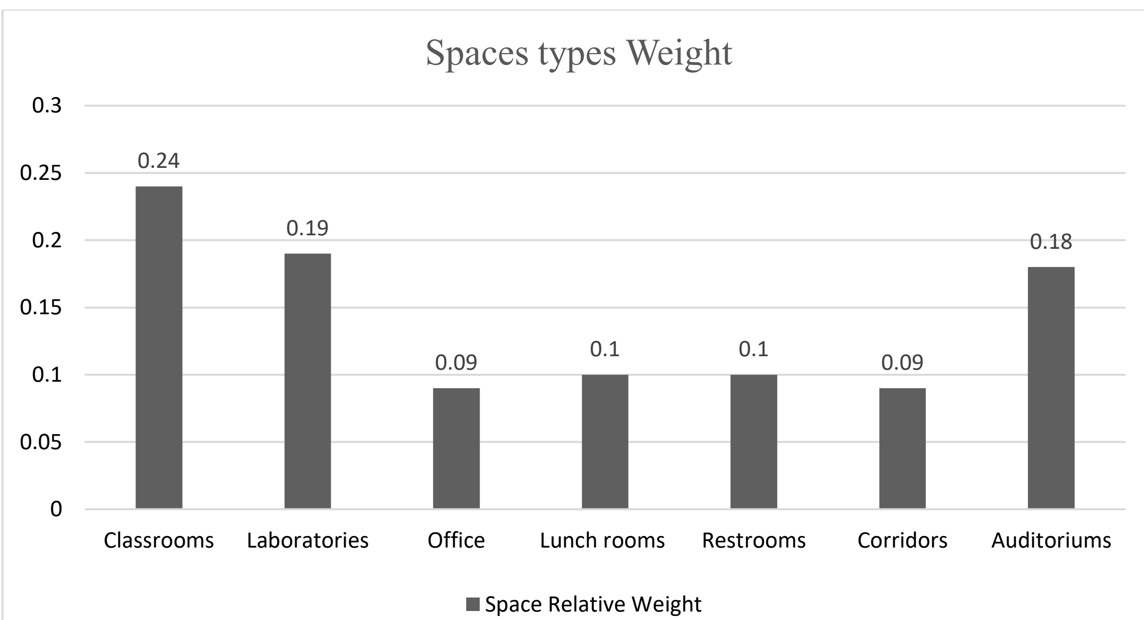

Figure 5-1 Spaces types weights from questionnaire Ewada (2014)

Another contributing factor is the space area, Applying Equation 3.1 would result in changing the weight. Based on a CAD drawing which was provided by Concordia, the laboratory space type showed the highest area percentage and was expected to have the highest weight.

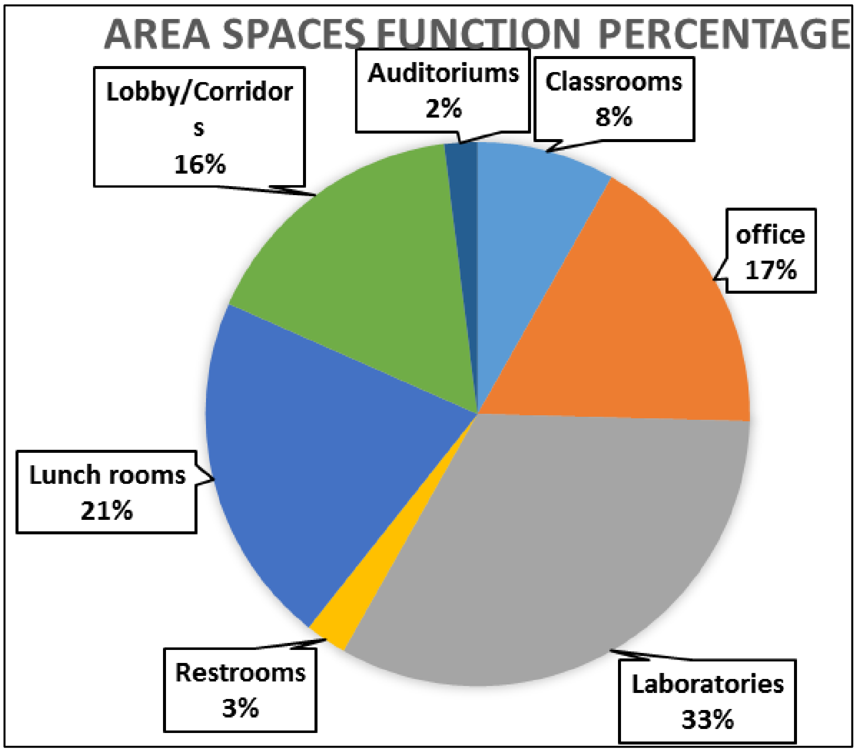

Figure 5-2 space types percentage

Figure 5.3 shows the Case study space type weight, based on the figure the laborite's space type has the highest weight, and the reason for that the percentage area compared to other is the highest. While the auditoriums become before last after being the third (18%) because the auditoriums area represent only 2% of the floor Area which is relatively small compared to other types. the calculation of each of space can be found in table 5.1.even whit two spaces which have the same type. a space that has more Area is more important. For example, a classroom whit 100 m2 would have 0.028265265. While a classroom whit 95 m2 would have 0.026897894.

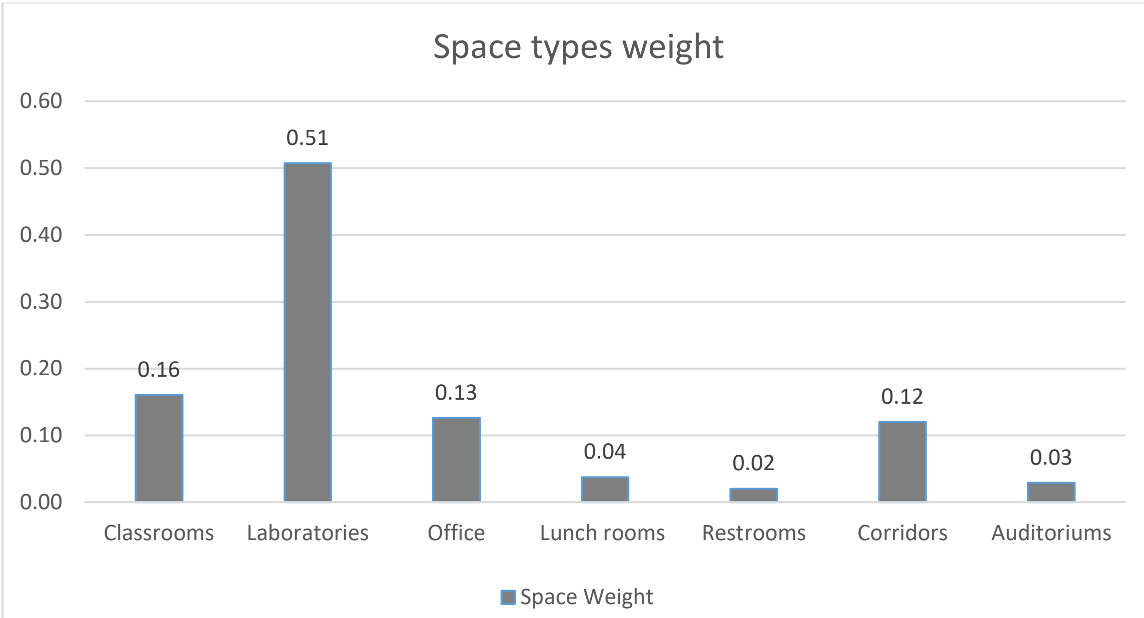

Figure 5-3 Case Study Space type weight

Table 5-1 Case Study Space weights

Space ID	Space type	Space area	Space type weight	space weight
1	classroom	95	0.24	0.026897894
2	classroom	98	0.24	0.027747301
3	classroom	99	0.24	0.028030437
4	classroom	100	0.24	0.028265265
5	classroom	110	0.24	0.026852002
6	office	8	0.09	0.000847958
7	office	10	0.09	0.001059947
8	office	8	0.09	0.000847958
9	office	11	0.09	0.001165942
10	office	8	0.09	0.000847958
11	office	11	0.09	0.001165942
12	office	12	0.09	0.001271937
13	office	9	0.09	0.000953953
14	office	11	0.09	0.001165942
15	office	10	0.09	0.001059947
16	office	10	0.09	0.001059947
17	office	10	0.09	0.001059947

18	office	10	0.09	0.001059947
19	office	9	0.09	0.000953953
20	office	8	0.09	0.000847958
21	office	13	0.09	0.001377932
22	office	13	0.09	0.001377932
23	office	11	0.09	0.001165942
24	office	12	0.09	0.001271937
25	office	12	0.09	0.001271937
26	office	9	0.09	0.000953953
27	office	13	0.09	0.001377932
28	office	8	0.09	0.000847958
29	office	9	0.09	0.000953953
30	office	13	0.09	0.001377932
31	office	12	0.09	0.001271937
32	office	10	0.09	0.001059947
33	office	9	0.09	0.000953953
34	office	8	0.09	0.000847958
35	office	8	0.09	0.000847958
36	office	12	0.09	0.001271937
37	office	9	0.09	0.000953953
38	office	13	0.09	0.001377932
39	office	9	0.09	0.000953953
40	office	9	0.09	0.000953953
41	office	12	0.09	0.001271937
42	office	8	0.09	0.000847958
43	office	10	0.09	0.001059947
44	office	12	0.09	0.001271937
45	office	12	0.09	0.001271937
46	office	9	0.09	0.000953953
47	office	11	0.09	0.001165942
48	office	10	0.09	0.001059947
49	office	12	0.09	0.001271937
50	office	9	0.09	0.000953953
51	office	8	0.09	0.000847958
52	office	10	0.09	0.001059947
53	office	13	0.09	0.001377932
54	office	11	0.09	0.001165942
55	office	12	0.09	0.001271937
56	office	12	0.09	0.001271937
57	office	12	0.09	0.001271937

58	office	11	0.09	0.001165942
59	office	9	0.09	0.000953953
60	office	13	0.09	0.001377932
61	office	9	0.09	0.000953953
62	office	10	0.09	0.001059947
63	office	8	0.09	0.000847958
64	office	13	0.09	0.001377932
65	office	9	0.09	0.000953953
66	office	8	0.09	0.000847958
67	office	8	0.09	0.000847958
68	office	8	0.09	0.000847958
69	office	8	0.09	0.000847958
70	office	8	0.09	0.000847958
71	office	11	0.09	0.001165942
72	office	11	0.09	0.001165942
73	office	10	0.09	0.001059947
74	office	9	0.09	0.000953953
75	office	8	0.09	0.000847958
76	office	11	0.09	0.001165942
77	office	13	0.09	0.001377932
78	office	13	0.09	0.001377932
79	office	11	0.09	0.001165942
80	office	13	0.09	0.001377932
81	office	12	0.09	0.001271937
82	office	10	0.09	0.001059947
83	office	10	0.09	0.001059947
84	office	9	0.09	0.000953953
85	office	10	0.09	0.001059947
86	office	13	0.09	0.001377932
87	office	13	0.09	0.001377932
88	office	11	0.09	0.001165942
89	office	12	0.09	0.001271937
90	office	13	0.09	0.001377932
91	office	8	0.09	0.000847958
92	office	8	0.09	0.000847958
93	office	9	0.09	0.000953953
94	office	10	0.09	0.001059947
95	office	9	0.09	0.000953953
96	office	12	0.09	0.001271937
97	office	11	0.09	0.001165942

98	office	10	0.09	0.001059947
99	office	12	0.09	0.001271937
100	office	12	0.09	0.001271937
101	office	13	0.09	0.001377932
102	office	9	0.09	0.000953953
103	office	13	0.09	0.001377932
104	office	11	0.09	0.001165942
105	office	8	0.09	0.000847958
106	office	10	0.09	0.001059947
107	office	9	0.09	0.000953953
108	lab	116	0.19	0.025956935
109	lab	117	0.19	0.026180702
110	lab	120	0.19	0.026852002
111	lab	120	0.19	0.026852002
112	lab	115	0.19	0.025733169
113	lab	117	0.19	0.026180702
114	lab	119	0.19	0.026628235
115	lab	116	0.19	0.025956935
116	lab	119	0.19	0.026628235
117	lab	118	0.19	0.026404469
118	lab	120	0.19	0.026852002
119	lab	117	0.19	0.026180702
120	lab	115	0.19	0.025733169
121	lab	118	0.19	0.026404469
122	lab	119	0.19	0.026628235
123	lab	120	0.19	0.026852002
124	lab	118	0.19	0.026404469
125	Restrooms	24	0.1	0.002826527
126	Restrooms	27	0.1	0.003179842
127	Restrooms	24	0.1	0.002826527
128	Restrooms	25	0.1	0.002944298
129	Restrooms	24	0.1	0.002826527
130	Restrooms	22	0.1	0.002590983
131	Lunch rooms	150	0.1	0.0759629
132	Lunch rooms	130	0.1	0.075374041
133	Lobby	1000	0.09	0.105994745
134	Auditoriums	120	0.18	0.025438739

5.2 Condition Prediction

In facility management case condition or performance, prediction is not easy considering that a building is not a single entity; a building consists of many components which all have a different service life. For example, most structural components have a very long service life while components like lamp has a small service life. In this research, a Weibull analysis was used for the deterioration of a building component. This approach has been used in the past for various building components (Grussing et al., 2006) and was adapted to this study. For many building components, early in their lifecycle, maximum condition is at the top and deteriorate with time and the Weibull distribution can easily represent such a situation.

One of the main advantages of the Weibull approach is the fact that to be solved only two pieces of information are required, the age and the current or initial condition of the component. Other commonly used methods, required the input of larger amount of data, thus making their development more time-consuming. A Building comprises of different architectural systems that have different service life, A Weibull technique is utilized for this purpose. Following the similar pattern as before in equation 3.5. In Figure 5.4, the deterioration curves of different systems are shown, as expected as the service life decrease as shown in table 5.2 the system is expected to deteriorate faster.

Based on figure 5.4 windows system represented by the blue line, has the most rapid deterioration. From the deterioration graphs of every system, their future severity can be easily extracted and based on these extracted values the assessment of each space assessment can be calculated.

Table 5-2 Systems service life (Grussing 2015)

System	Service life
Ceiling	36
Doors	32
Floors	28
Windows	22
Walls	34

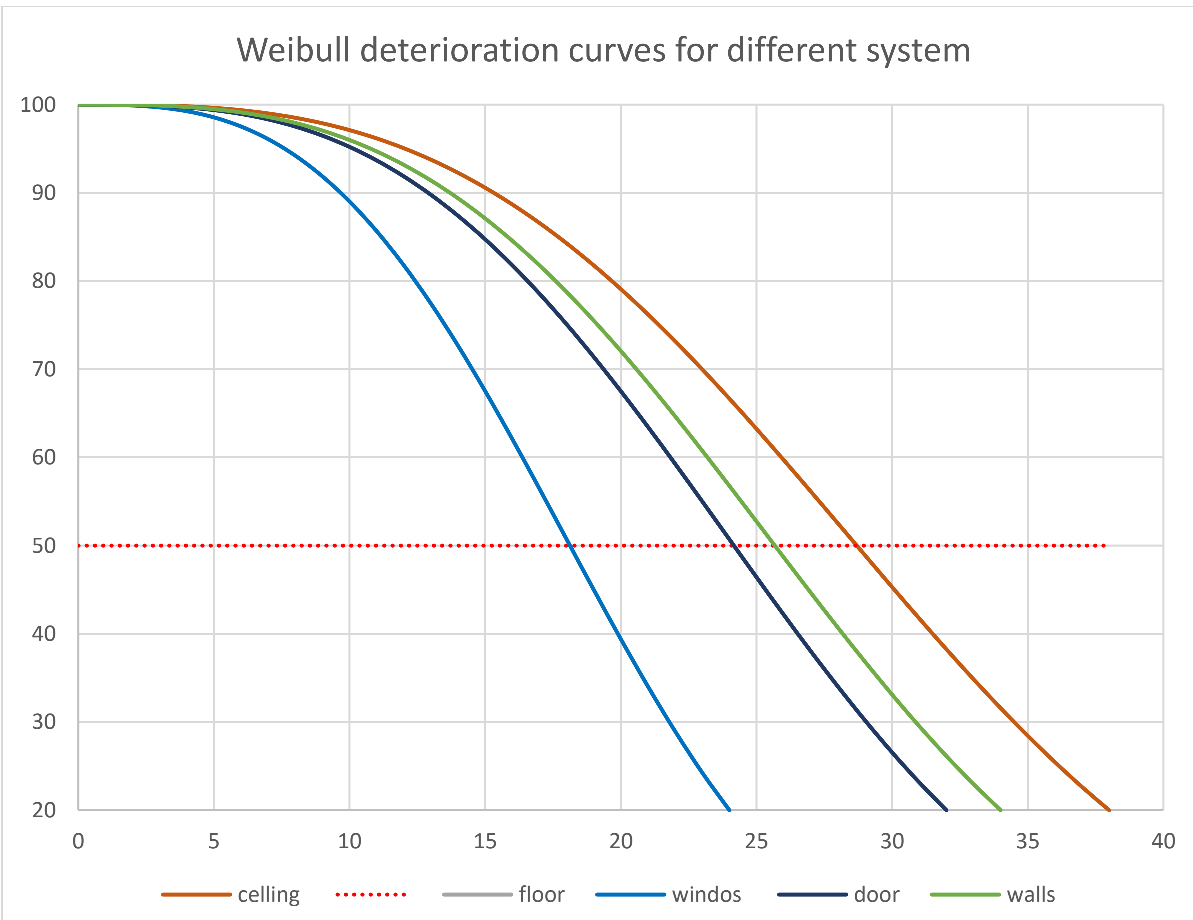

Figure 5-4 Weibull deterioration curves for different system

Figure 5.5 shows the Weibull deterioration curves for door system Based on figure 5.5 as the service life increase the deterioration rate decrease.

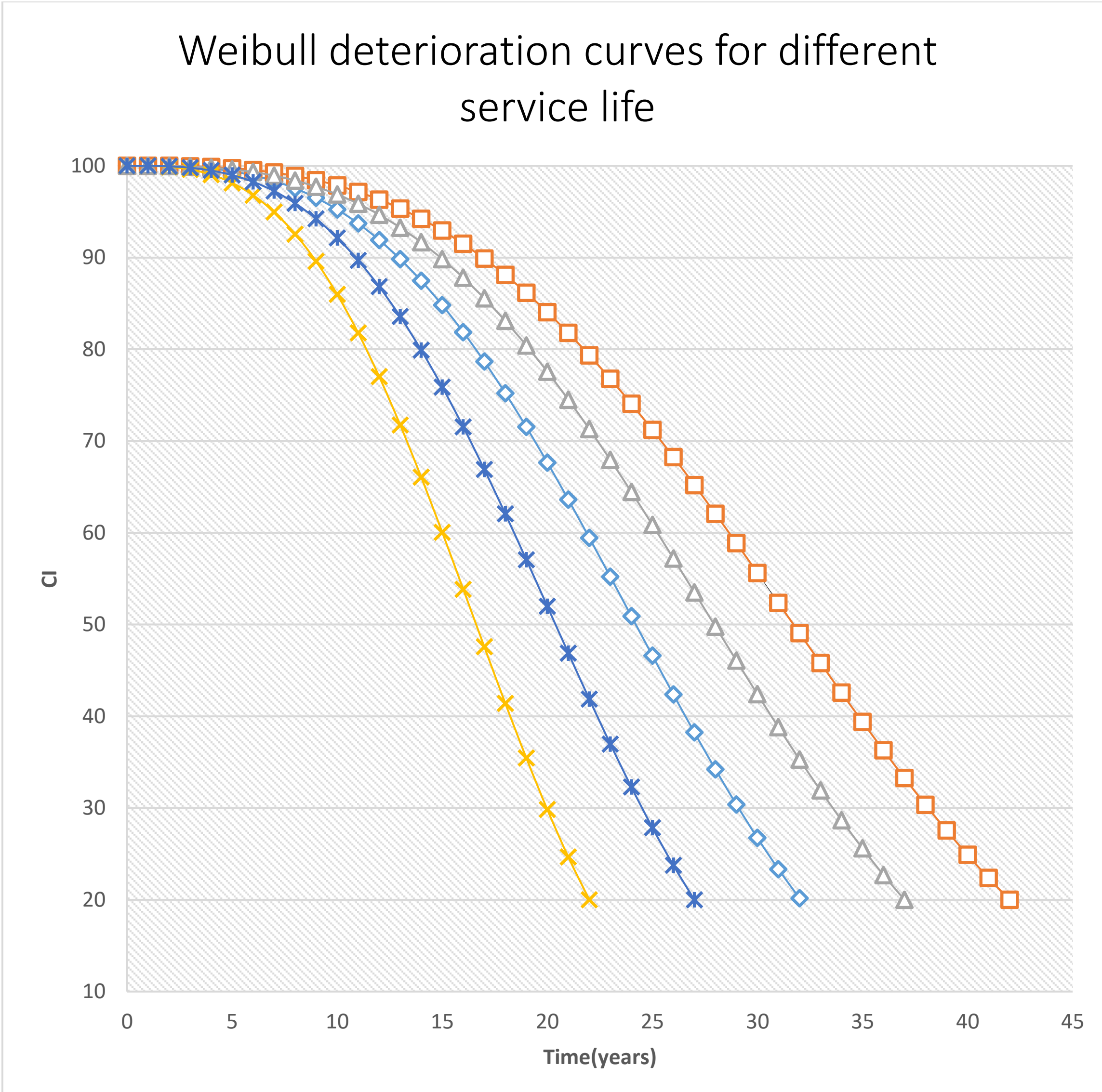

Figure 5-5 Weibull deterioration curves for different service life

5.3 Sensitivity analysis

Sensitivity analysis is an approach used to identify the degree of uncertainty in the outcome of a mathematical system by examining the sources of uncertainty in input parameters. This technique evaluates the impact of an independent variable (input parameter) on a dependent variable (outcome). In this research, a sensitivity analysis was evaluated by incrementing the estimated service life in pre-defined five-year steps positively and negatively from the basic estimated service life. The analysis shows that a change in the estimated service life will have an impact on the maintenance plan. Figure 5.6 shows the condition-cost trade-off when service life is changed by five years plus or minus the basic estimated service life. The blue ‘o’ solutions in the figure represent the Pareto-optimum solutions obtained by particle swarm optimization. The yellow ‘×’ solutions represent the Pareto solutions if the service life of the system is 42 years, while the blue ‘×’ solutions represent the Pareto solutions if the service life of the system is 22 years. The estimated service life of a system will affect both the system condition and maintenance cost. The maximum and minim conditions and cost obtained from each Pareto frontier. As the estimated service life increases, the need for and cost of maintenance decreases, as shown in Table 5.3.

Table 5-3 Max and min CI and cost for Each Pareto frontier

Service Life	Max Condition	Min Condition	Max maintenance Cost	Min maintenance Cost
42	2.74	2.59	60,677.67	48,134.48
37	4.11	3.88	80,903.56	64,179.30
32	5.49	5.17	107,871.41	85,572.40
27	8.23	7.76	134,839.26	106,965.50
22	12.34	11.64	168,549.08	133,706.88

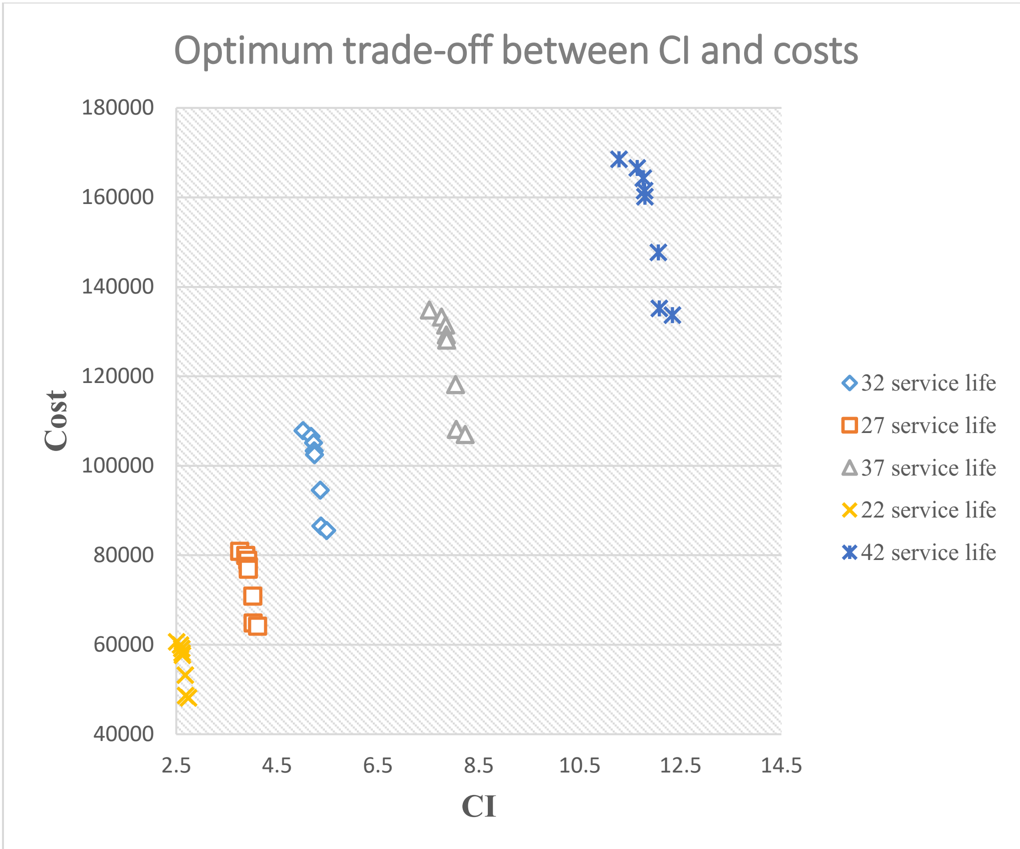

Figure 5-6 Optimum trade-off between CI and costs based on changing estimated system service life

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

This research proposes a Maintenance Optimization Model for Buildings that account for and manage the maintenance of the building according to its spaces. The methodology starts with the space-based condition assessment of the building then continues with the development of a condition prediction model, which is done in the system level based on Weibull theory and results in the construction of component deterioration curves. The last stage is the multi-objective particle swarm algorithm was implemented to find the most favorable maintenance plan based on two objective functions: the minimization of the total maintenance cost and the maximization of the space-based condition assessment.

Additionally, a case study, which is the third floor of EV buildings at Concordia University in Montreal, was utilized to implement the developed optimization model. The data of the buildings was gathered from the Concordia Facility Management Office. The CAD plans, which was gathered from the Facility Management Office, was used to develop the BIM model in Revit software to help in the space-based condition assessment and the repair cost model. After that Weibull technique was utilized to predict the future condition of walls, doors, windows, floors, and ceilings. The results of the condition prediction model showed that the window system type has the most rapid deterioration. As well, as the service life decrease, the system is expected to deteriorate faster.

Next, particle swarm evolutionary optimization to provide the decision-makers with a sets of alternatives to optimize the overall building condition and life cycle cost .which was developed with two software, Excel spreadsheets and Matlab. The inputs of the model were space weight, systems conditions, systems weights, systems maintenances cost, defects severity, defect type weights, minimum acceptable condition level, budget constraint, and analysis period. The output of the model as illustrated in Chapter 4 was non-dominated solutions. Each solution contains 3350 maintenance action that were determined by the optimization model. A snapshot of the maintenance plan was shown in table 4.3 while the rest of the maintenance plane was shown on appendix F. In the optimal maintenance plan found there is a heavier investment in the maintenance of all systems at the beginning of the plan period compared with the end of period.

6.2 Research Contributions

The main Contribution is the development of the Space based maintenance management optimization model for buildings where the space type and space area are to be considered whiten the optimization model. This model is flexible when compared to other models since it treats each space individually and considers the type of tasks held inside that space. Also, it can be adapted to suit any type of facility. This model would be extremely useful in the systematization and optimization of maintenance strategies avoiding the huge expenses by decreasing the cost associated with maintenance through the suggestion of best maintenance actions which would keep the building in an acceptable condition with minimum cost because it considers the space type which led to neglect the unneeded maintenance actions. In addition, facilities managers can change some variables such as spaces type, spaces area, spaces condition, systems inside the spaces, current conditions of systems, defect severity, defect type weights, minimum acceptable service or condition level, maintenance cost, budget constraint, and analysis period in the model to follow any specific codes, standards, and benchmarks as required, as well as to represent the identified concepts, goals to be fulfilled, other building features, and attributes to be considered in other building types.

6.3 Limitations and Suggestions for Future Work

This research offers the following limitations and recommendations for future work:

1- The model did not consider the outdoor spaces, the outdoor spaces are important for the users of the buildings, for example in the case of educational building the outdoor spaces are an influential factor for student life and Social interaction between students through students flow in outdoor spaces. An improvement to the model can be done by considering outdoor spaces.

2- One of the enhancement could be the consideration of other building systems such as mechanical, electrical and structural category inside building spaces.

3- The methodology could be implemented to other buildings types, because other building types have their own nature and properties.

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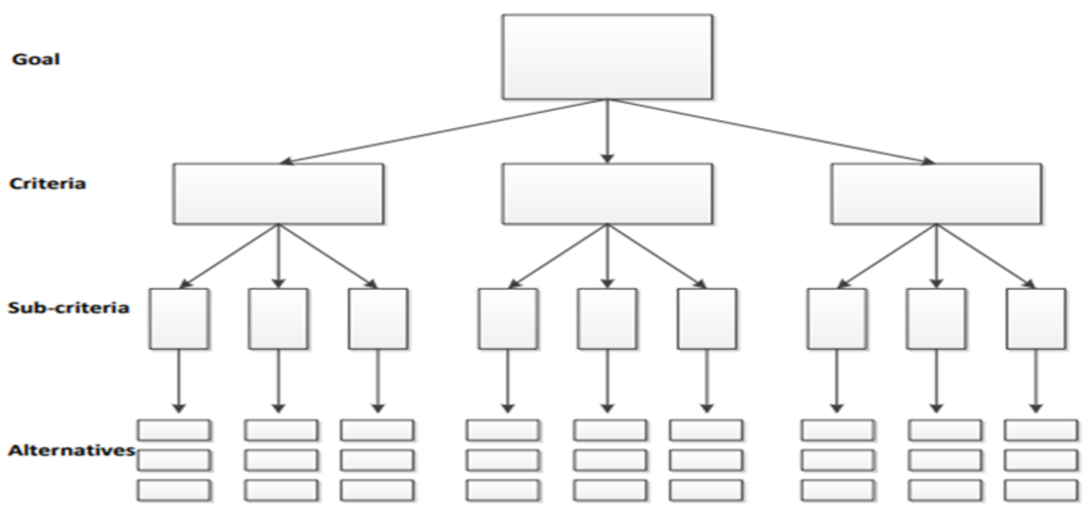
Appendix A

Analytical hierarchy processes

Saaty has developed the AHP in 1971 to help people prioritize alternative based on their relative importance in the decision-making problems since then it has been used extensively in a wide range of prioritization problem (Lee et al. 2001). The AHP start by the division of the decision problem into a hierarchy which should be based on the expert experience and all essential elements relevant to the problem included (Chen 2006). The hierarchy usually constructed from the top (goal) through the immediate level (criteria and sub-criteria that subsequent levels depend on), and on to the lowest level (alternatives) as shown in fig 2 (Gkountis 2014).



Hierarchical Structure of the Decision Problem (Gkountis 2014)

Next step is the data collection and pairwise comparisons in order to determine the relative importance of the elements in each level. The relative importance for each criteria is different from each another and from the sub-criteria and each alternative rates differently on each criteria. According to Chen (2006), Pairwise comparison analysis involves three.

The first step is developing a comparison matrix at each level of the hierarchy starting from the second level and working down. The next step is computing the relative weights for each element of the hierarchy. Finally estimating the consistency ratio to check the consistency of the judgment.

$$\widetilde{\boldsymbol{A}} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix}$$

The comparison matrix general form can be given matrix A is an n×n real matrix, each entry ajk of the matrix A represents the importance of the jth criterion where m is the number of evaluation criteria considered. The relative importance between the two criteria is measured according to a numerical scale from 1 to 9, as shown in the Table below

Pairwise Comparison - Saaty's Fundamental Scale

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

The computation of the weights involves two steps. First, the pairwise comparison matrix, A = [aij] nxn, is normalized by equation

$$a_{ij}^* = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

And then the weights are computed by equation (2).

$$w_i = \frac{\sum_{j=1}^{n} a_{ij}^*}{n}$$

Then To calculate the CR, the consistency index (CI) for each matrix of order n can be obtained from the equation.

$$CI = \frac{\lambda - n}{n - 1}$$

Finally, CR can be calculated by dividing CI over RI

Where RI is the random consistency index obtained from a randomly generated pairwise comparison matrix.

Appendix B

Particle swarm optimization

Particle swarm was first developed by Kennedy and Eberhart in 1995. The main idea behind this optimization that it is to mimic the behavior of a group of animals such as birds or fishes when searching for food. In this algorithm, each particle in the group moves with a velocity through the search space. The position of each particle in the search space is modified according to the experiences of the particle and its friends. The particles move towards the global minimum, while still searching a wide space around the optimal solution. In addition, each particle represents a possible solution of an optimization problem which moves in the search space, and this movement is achieved by an operator that is directed by a local and by social elements. It is easy to implement, so it can be applied both in scientific research and engineering problems (Vrahatis 2002). It has a limited number of parameters and the impact of parameters on the solutions is small compared to other optimization techniques. Moreover, Previous studies (Kennedy 2007) identified that PSO has faster convergence rates and more competitive detective capabilities than other EA approaches. Furthermore, previous researcher Koay (2002) compared the PSO against GA to a practical scheduling and optimization problem and prove that the PSO algorithm yield superior performance.

The calculation in the PSO algorithm is very simple. There are some techniques which ensure convergence and the optimum value of the problem calculates easily within a short time. PSO is less dependent on a set of initial points than other optimization techniques. It is conceptually very simple (Talukder 2011). Each particle is assumed to a position (location) and a velocity. The location of each particle is represented by

$Xi\ (t) = \{X1(t), X2(t), \ldots, Xn(t)\}$ and a velocity represented by $V_i(t) = \{V_1(t), V_2(t), \ldots, V_n(t)\}$. Each particle updates it is location and velocity by using the following equations.

$$Vi,j(t+1)=w\ Vi,j(t)+r1\ c1\ [Pbesti,j(t)-Xi,j(t)]+r2\ c2\ [Gbest(t)-Xi,j(t)]$$

And

$$Xi, j\ (t+1) = Xi, j\ (t) + Vi, j\ (t+1)$$

Where

(t) = local or personal best position for particle i at iteration t;

$Gbest\ (t)$ = global best position or particle leader at iteration t;

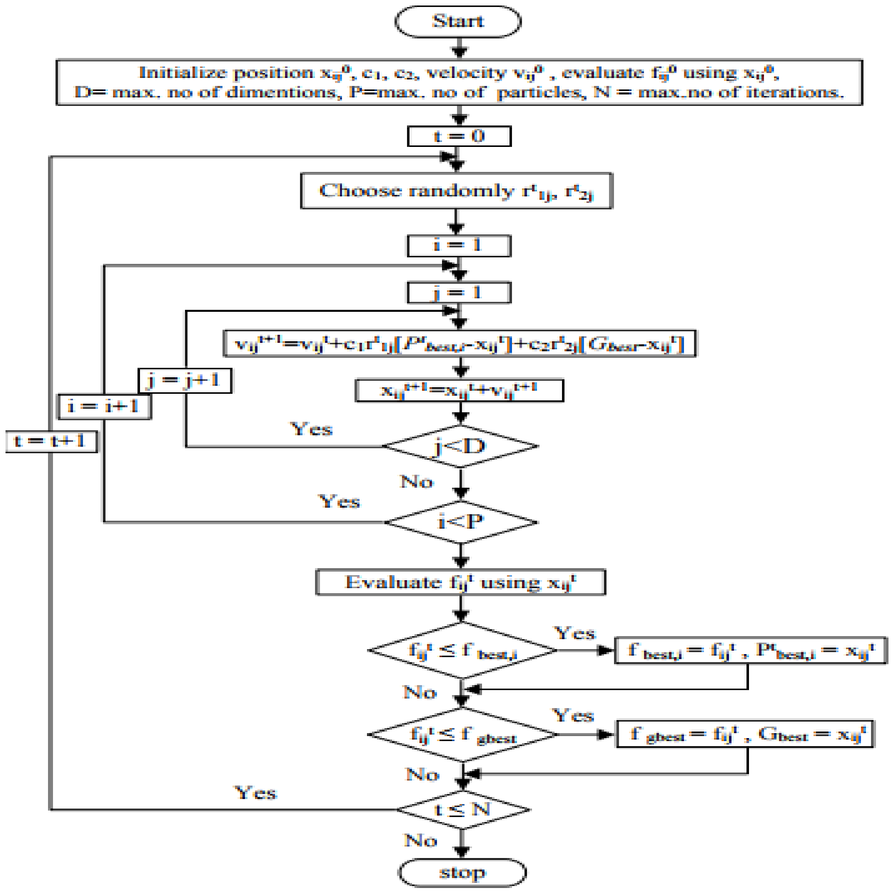
w = the inertia weight of the particle;

$c1$ and $c2$ = acceleration coefficients (positive constants);

$r1$ and $r2$ = random numbers within [0, 1].

At the beginning a number of particles will be assumed then a random number which represent a particle location and possible solution from the solution space should be assigned to each particle, after that all particle will be evaluated based on the objective function and the particle whit the best location $Gbest$ (t) should lead the other particle to its location. This movement of these particle is governed by the equations, it should be noticed that whit each movement the particle whit the best location will lead the other particle to it location until the best location is found. These steps can be modeled by a flowchart below.

In each movement the leader particle $Gbest$ (t) guides the particles to move to the best position at that generation, also a particles location and velocity memory is updated. For each particle in the swarm, its performance is estimated according to the fitness or objective of the optimization problem. The inertia weight w is used to regulate the effect of the previous velocities on the current velocity. This has the effect of producing a trade-off between the global and local exploration abilities of the particles (de Carvalho and Pozo, 2012). Some PSO Algorithm Parameters that can affect the accuracy and PSO performance which include Swarm size (as the number of particle increase the accuracy increase), Iteration numbers and velocity component.



Particle swarm algorithm steps

In multi-objective optimization, the case is different there is a need is to satisfy the two or more-objective function which may or may not conflict whit each other. Also, to determine the best global particle "leader" that should be redefined to obtain a set of optimal solutions called the Pareto-front of which each member is not dominated by others at each generation (Pham 2012), so it is essential to locate and find a decent trade-off of solutions that represent a compromise between the objectives (de Carvalho and Pozo, 2012).

In multi guider multi-objective optimization particle swarm (MGC-MOPSO) algorithm proposed by Pham (2012) two guider partials are suggested, other than one particle. The guider particle has a global optimal location where the second guider particle is controlled by a cross-searching factor to control the effect of the second guider to make a good distribution of the solutions over the whole Pareto-front concerning all objectives and to provide a good diversity over the whole Pareto-front regarding all objectives. (Pham et al., 2012). Another developed PSO method was developed by Kennedy (1995) which called bare-bones particle swarm optimization (BBPSO), which later was extends to multi-objective optimization problems by Zhang (2012) where its main feature is a designed parameter-free multi-objective optimization (Zhang et al., 2012). The BBPSO proposed a Gaussian distribution based on global best position ((t)) and local best position (Pbi, (t)) rather than the particle velocity. The particle position is given by (Zhang et al., 2012).

$$X_{i,j}\,(t+1) = \begin{cases} N(\frac{Pb_{i\cdot j}(t)+Gb_j(t)}{2}, \left|Pb_{i,j}\,(t) + Gb_j(t)\right|) & if\ U(0,1) < 0.5 \\ Pb_{i,j}\,(t) & \end{cases} \quad \text{Equation 0-1}$$

Where

$$N(\frac{Pb_{i\cdot j}\,(t) + Gb_j(t)}{2}, \left|Pb_{i,j}\,(t) + Gb_j(t)\right|)$$

Is a Gaussian distribution and U (0, 1) is a uniform distribution between 0 and 1.

From the above equations, the particle positions in any dimensions have a 50% chance to update and change to the corresponding personal best position (Zhang et al., 2012). Since no information of inertia weights and acceleration coefficients are not needed The BBPSO is advantageous. The main feature of BBPSO is that a particle can update without needing to tune up control parameters. Moreover, to avoid early convergence and increase the search capability, the effect mutation operator on all particles in the swarm is changeable based on the number of generations. Another feature of BBPSO is the updating of the global best particle based on the diversity of non-dominated solutions. Furthermore, it has good performance in multi-objective optimization problems and is also easy to implement (Zhang et al., 2012).

Appendix C

Spaces area and type for the EV building third floor

Space ID	Space type	Space area	Space weight	Total Area relative weight
1	classroom	95	0.24	0.026897894
2	classroom	98	0.24	0.027747301
3	classroom	99	0.24	0.028030437
4	classroom	100	0.24	0.028265265
5	classroom	95	0.24	0.026852002
6	office	8	0.09	0.000847958
7	office	10	0.09	0.001059947
8	office	8	0.09	0.000847958
9	office	11	0.09	0.001165942
10	office	8	0.09	0.000847958
11	office	11	0.09	0.001165942
12	office	12	0.09	0.001271937
13	office	9	0.09	0.000953953
14	office	11	0.09	0.001165942
15	office	10	0.09	0.001059947
16	office	10	0.09	0.001059947
17	office	10	0.09	0.001059947
18	office	10	0.09	0.001059947
19	office	9	0.09	0.000953953
20	office	8	0.09	0.000847958
21	office	13	0.09	0.001377932
22	office	13	0.09	0.001377932
23	office	11	0.09	0.001165942
24	office	12	0.09	0.001271937
25	office	12	0.09	0.001271937
26	office	9	0.09	0.000953953
27	office	13	0.09	0.001377932
28	office	8	0.09	0.000847958
29	office	9	0.09	0.000953953
30	office	13	0.09	0.001377932

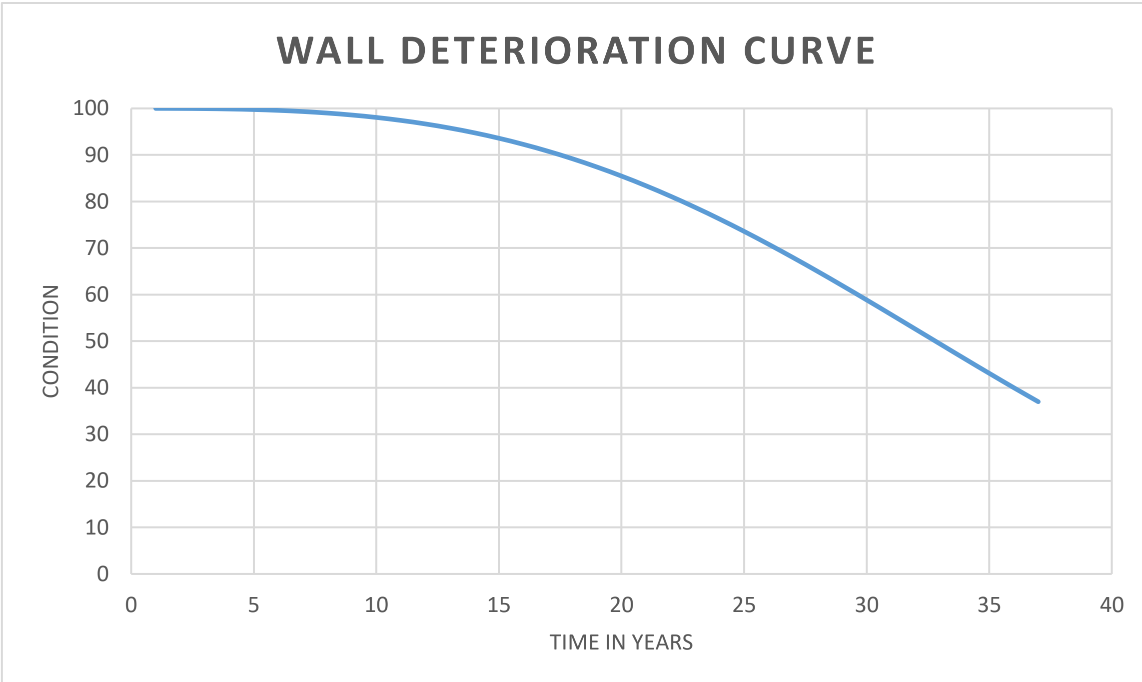
31	office	12	0.09	0.001271937
32	office	10	0.09	0.001059947
33	office	9	0.09	0.000953953
34	office	8	0.09	0.000847958
35	office	8	0.09	0.000847958
36	office	12	0.09	0.001271937
37	office	9	0.09	0.000953953
38	office	13	0.09	0.001377932
39	office	9	0.09	0.000953953
40	office	9	0.09	0.000953953
41	office	12	0.09	0.001271937
42	office	8	0.09	0.000847958
43	office	10	0.09	0.001059947
44	office	12	0.09	0.001271937
45	office	12	0.09	0.001271937
46	office	9	0.09	0.000953953
47	office	11	0.09	0.001165942
48	office	10	0.09	0.001059947
49	office	12	0.09	0.001271937
50	office	9	0.09	0.000953953
51	office	8	0.09	0.000847958
52	office	10	0.09	0.001059947
53	office	13	0.09	0.001377932
54	office	11	0.09	0.001165942
55	office	12	0.09	0.001271937
56	office	12	0.09	0.001271937
57	office	12	0.09	0.001271937
58	office	11	0.09	0.001165942
59	office	9	0.09	0.000953953
60	office	13	0.09	0.001377932
61	office	9	0.09	0.000953953
62	office	10	0.09	0.001059947
63	office	8	0.09	0.000847958
64	office	13	0.09	0.001377932
65	office	9	0.09	0.000953953
66	office	8	0.09	0.000847958
67	office	8	0.09	0.000847958
68	office	8	0.09	0.000847958
69	office	8	0.09	0.000847958
70	office	8	0.09	0.000847958

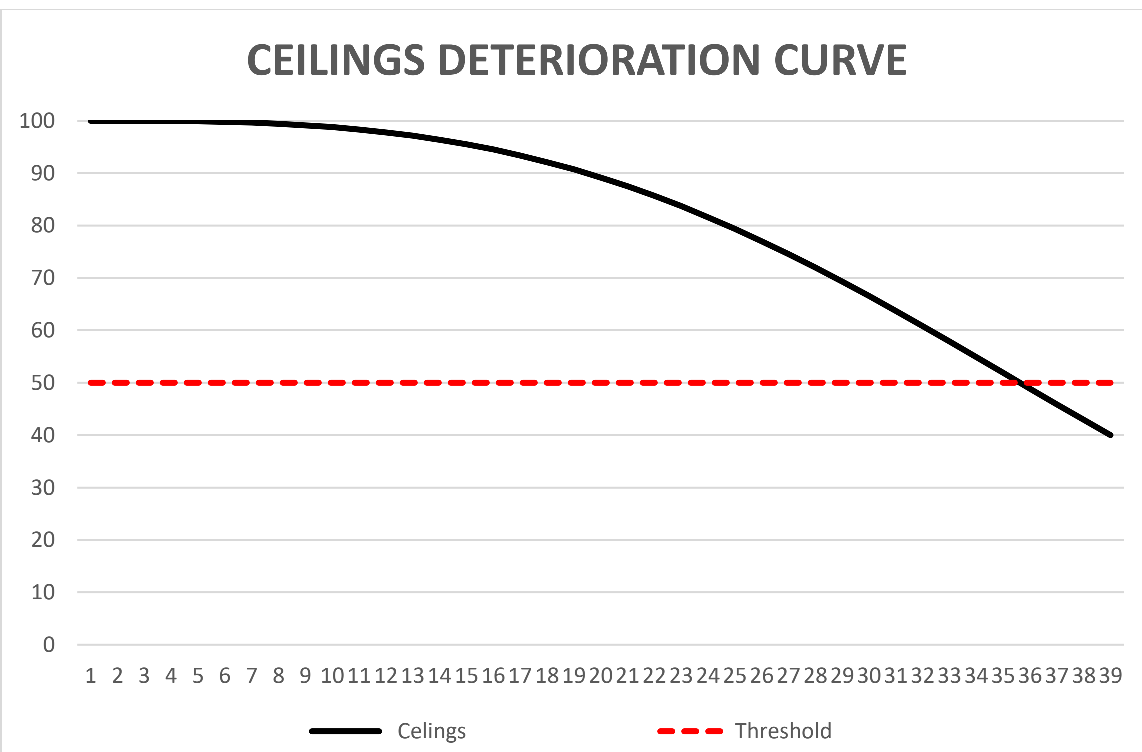
71	office	11	0.09	0.001165942
72	office	11	0.09	0.001165942
73	office	10	0.09	0.001059947
74	office	9	0.09	0.000953953
75	office	8	0.09	0.000847958
76	office	11	0.09	0.001165942
77	office	13	0.09	0.001377932
78	office	13	0.09	0.001377932
79	office	11	0.09	0.001165942
80	office	13	0.09	0.001377932
81	office	12	0.09	0.001271937
82	office	10	0.09	0.001059947
83	office	10	0.09	0.001059947
84	office	9	0.09	0.000953953
85	office	10	0.09	0.001059947
86	office	13	0.09	0.001377932
87	office	13	0.09	0.001377932
88	office	11	0.09	0.001165942
89	office	12	0.09	0.001271937
90	office	13	0.09	0.001377932
91	office	8	0.09	0.000847958
92	office	8	0.09	0.000847958
93	office	9	0.09	0.000953953
94	office	10	0.09	0.001059947
95	office	9	0.09	0.000953953
96	office	12	0.09	0.001271937
97	office	11	0.09	0.001165942
98	office	10	0.09	0.001059947
99	office	12	0.09	0.001271937
100	office	12	0.09	0.001271937
101	office	13	0.09	0.001377932
102	office	9	0.09	0.000953953
103	office	13	0.09	0.001377932
104	office	11	0.09	0.001165942
105	office	8	0.09	0.000847958
106	office	10	0.09	0.001059947
107	office	9	0.09	0.000953953
108	lab	116	0.19	0.025956935
109	lab	117	0.19	0.026180702
110	lab	120	0.19	0.026852002

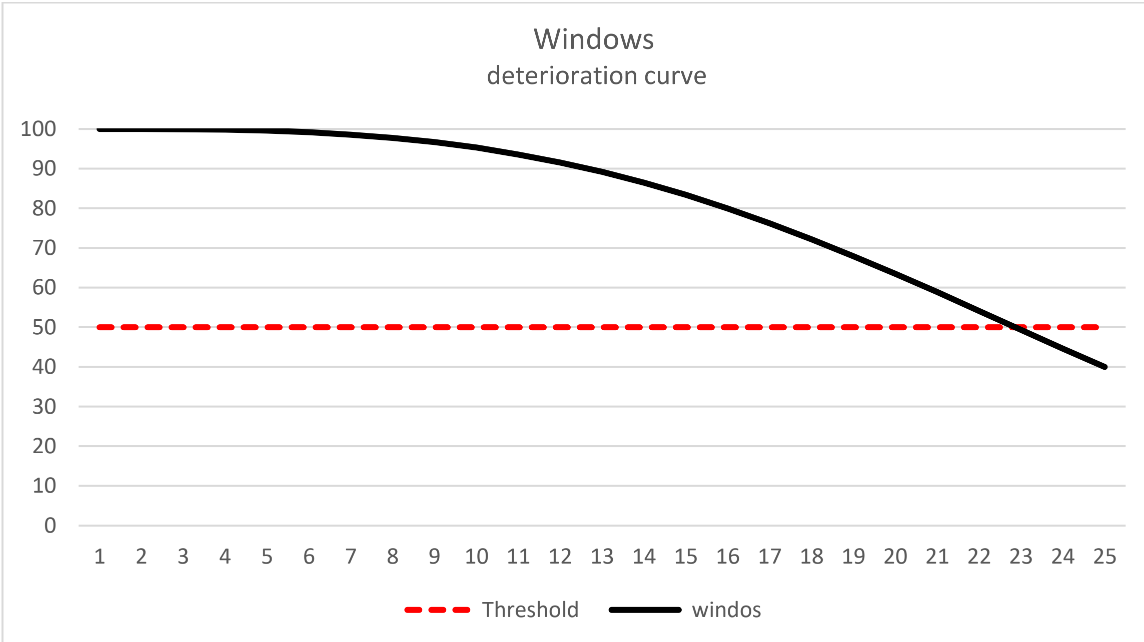
111	lab	120	0.19	0.026852002
112	lab	115	0.19	0.025733169
113	lab	117	0.19	0.026180702
114	lab	119	0.19	0.026628235
115	lab	116	0.19	0.025956935
116	lab	119	0.19	0.026628235
117	lab	118	0.19	0.026404469
118	lab	120	0.19	0.026852002
119	lab	117	0.19	0.026180702
120	lab	115	0.19	0.025733169
121	lab	118	0.19	0.026404469
122	lab	119	0.19	0.026628235
123	lab	120	0.19	0.026852002
124	lab	118	0.19	0.026404469
125	Restrooms	24	0.1	0.002826527
126	Restrooms	27	0.1	0.003179842
127	Restrooms	24	0.1	0.002826527
128	Restrooms	25	0.1	0.002944298
129	Restrooms	24	0.1	0.002826527
130	Restrooms	26	0.1	0.002590983
131	Lunch rooms	145	0.1	0.0759629
132	Lunch rooms	140	0.1	0.075374041
133	Lobby	1000	0.09	0.105994745
134	Auditoriums	120	0.18	0.025438739

Appendix D

Deterioration curves






Windows
deterioration curve
100
90
80
70
60
50
40
30
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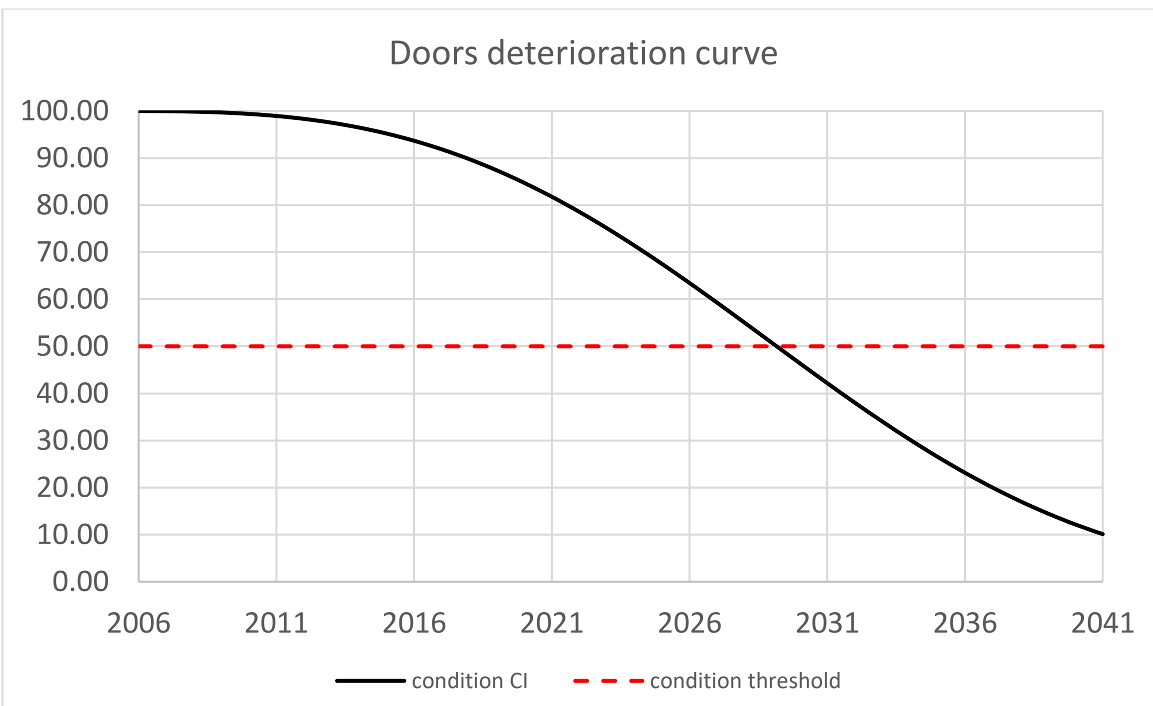
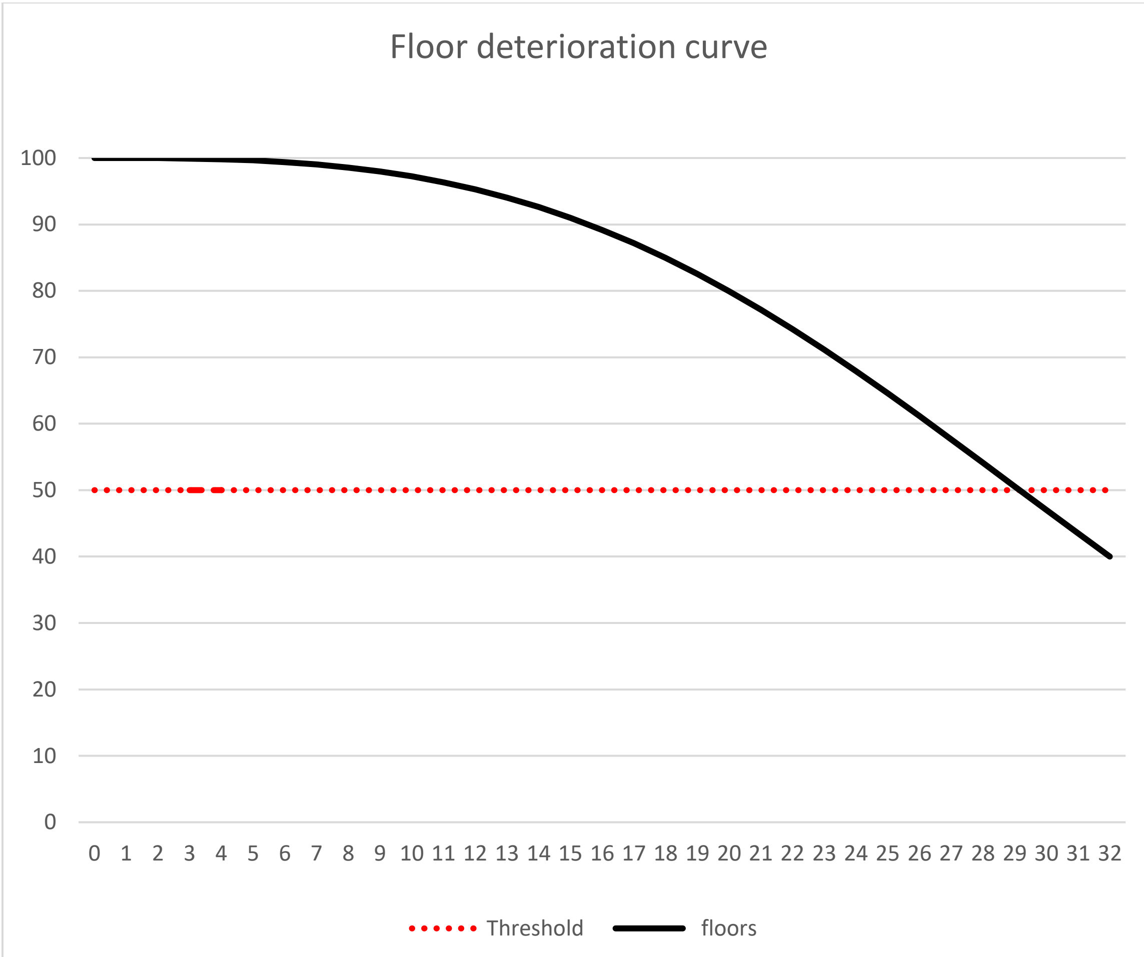
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Threshold
windos


Doors deterioration curve
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
2006 2011 2016 2021 2026 2031 2036 2041
condition CI
condition threshold



System	Design life	initial condition	β	α	time years	condition CI (t)	condition (t)	defect type	defect weight	defect severity
walls		100	37.07116459	3	0	100	0	Appearance	54	0
								Damage	38	0
								Performance	8	0
		100	37.07116459	3	1	99.99803715	0	Appearance	54	1.89735E-06
								Damage	38	3.09648E-05
								Performance	8	8.54663E-05
		100	37.07116459	3	2	99.98429828	0	Appearance	54	0.000252876
								Damage	38	3.40613E-05

								Performance	8	9.40129E-05
		100	37.07116459	3	3	99.94701658	0	Appearance	54	0.000936357
								Damage	38	4.56948E-05
								Performance	8	0.000103414
		100	37.07116459	3	4	99.87445526	0	Appearance	54	0.001625777
								Damage	38	0.000954941
								Performance	8	0.000183128
		100	37.07116459	3	5	99.75494214	0	Appearance	54	0.003515586
								Damage	38	0.001413757
								Performance	8	0.00018668
		100	37.07116459	3	6	99.57691783	0	Appearance	54	0.006567797
								Damage	38	0.001760986
								Performance	8	0.000187955
		100	37.07116459	3	7	99.32899729	0	Appearance	54	0.011032213
								Damage	38	0.001937085
								Performance	8	0.00020675
		100	37.07116459	3	8	99.00004422	0	Appearance	54	0.01698456
								Damage	38	0.002130794
								Performance	8	0.000227425
		100	37.07116459	3	9	98.57925768	0	Appearance	54	0.024623589
								Damage	38	0.002343873
								Performance	8	0.000250167
		100	37.07116459	3	10	98.05626987	0	Appearance	54	0.034139903

								Damage	38	0.002578 26
								Performance	8	0.000275 184
		100	37.0711 6459	3	11	97.42125 395	0	Appearance	54	0.045713 947
								Damage	38	0.002836 086
								Performance	8	0.000302 703
		100	37.0711 6459	3	12	96.66504 033	0	Appearance	54	0.059513 842
								Damage	38	0.003119 695
								Performance	8	0.000332 973
		100	37.0711 6459	3	13	95.77923 947	0	Appearance	54	0.075693 095
								Damage	38	0.003431 664
								Performance	8	0.000366 27
		100	37.0711 6459	3	14	94.75636 905	0	Appearance	54	0.094388 226
								Damage	38	0.003774 831
								Performance	8	0.000402 897
		100	37.0711 6459	3	15	93.58998 295	0	Appearance	54	0.115706 952
								Damage	38	0.004165 681
								Performance	8	0.000443 219
		100	37.0711 6459	3	16	92.27479 919	0	Appearance	54	0.139762 501
								Damage	38	0.004582 249
								Performance	8	0.000487 541
		100	37.0711 6459	3	17	90.80682 365	0	Appearance	54	0.166617 555
								Damage	38	0.005040 474
								Performance	8	0.000536 295

		100	37.07116459	3	18	89.18346632	10.57147582	Appearance	54	0.003515586
								Damage	38	0.001413757
								Performance	8	0.00018668
		100	37.07116459	3	19	87.40364642	12.35129572	Appearance	54	0.003515586
								Damage	38	0.001413757
								Performance	8	0.00018668
		100	37.07116459	3	20	85.46788298	14.53015417	Appearance	54	0
								Damage	38	5.16539E-05
								Performance	8	0
		100	37.07116459	3	21	83.37836723	16.60593105	Appearance	54	0.000290773
								Damage	38	5.12394E-14
								Performance	8	2.91847E-14
		100	37.07116459	3	22	81.1390133	18.80800328	Appearance	54	0.000610056
								Damage	38	0.000491323
								Performance	8	0.000171268
		100	37.07116459	3	23	78.75548432	21.11897094	Appearance	54	0.001625777
								Damage	38	0.000954941
								Performance	8	0.000183128
		100	37.07116459	3	24	76.23519087	23.51975127	Appearance	54	0.003515586
								Damage	38	0.001413757
								Performance	8	0.00018668
		100	37.07116459	3	25	73.58725965	26.16768249	Appearance	54	0.003515586
								Damage	38	0.001413757

								Performance	8	0.00018668
		100	37.07116459	3	26	70.82247079	29.17752921	Appearance	54	0
								Damage	38	0
								Performance	8	0
		100	37.07116459	3	27	67.95316277	32.04487438	Appearance	54	0
								Damage	38	5.16539E-05
								Performance	8	0
		100	37.07116459	3	28	64.99310504	34.99119324	Appearance	54	0.000290773
								Damage	38	5.12394E-14
								Performance	8	2.91847E-14
		100	37.07116459	3	29	61.95733921	37.98967737	Appearance	54	0.000610056
								Damage	38	0.000491323
								Performance	8	0.000171268
		100	37.07116459	3	30	58.86199063	41.01246463	Appearance	54	0.001625777
								Damage	38	0.000954941
								Performance	8	0.000183128
		100	37.07116459	3	31	55.72405321	44.03088893	Appearance	54	0.003515586
								Damage	38	0.001413757
								Performance	8	0.00018668
		100	37.07116459	3	32	52.56115135	47.19379079	Appearance	54	0.003515586
								Damage	38	0.001413757
								Performance	8	0.00018668
		100	37.07116459	3	33	49.39128351	50.60675364	Appearance	54	0
								Damage	38	5.16539E-05

								Performance	8	0
		100	37.07116459	3	34	46.23255312	53.75174516	Appearance	54	0.000290773
								Damage	38	5.12394E-14
								Performance	8	2.91847E-14
		100	37.07116459	3	35	43.10289274	56.84412384	Appearance	54	0.000610056
								Damage	38	0.000491323
								Performance	8	0.000171268
		100	37.07116459	3	36	40.01978815	59.85466711	Appearance	54	0.001625777
								Damage	38	0.000954941
								Performance	8	0.000183128
		100	37.07116459	3	37	37.00000925	62.75493289	Appearance	54	0.003515586
								Damage	38	0.001413757
								Performance	8	0.00018668

Door deterioration with time

β	α	time (years)	condition CI	threshold
27.357	3	2005	100	50
27.357	3	2006	99.99511591	50
27.357	3	2007	99.96093393	50
27.357	3	2008	99.86821317	50
27.357	3	2009	99.68789843	50
27.357	3	2010	99.39133331	50
27.357	3	2011	98.95055551	50
27.357	3	2012	98.33866983	50
27.357	3	2013	97.53029189	50
27.357	3	2014	96.50205213	50
27.357	3	2015	95.23314631	50
27.357	3	2016	93.70591478	50
27.357	3	2017	91.9064293	50
27.357	3	2018	89.82506243	50
27.357	3	2019	87.45701218	50
27.357	3	2020	84.80275239	50
27.357	3	2021	81.86837908	50
27.357	3	2022	78.66582404	50
27.357	3	2023	75.21290972	50
27.357	3	2024	71.53322459	50
27.357	3	2025	67.65580443	50
27.357	3	2026	63.61461419	50
27.357	3	2027	59.4478343	50
27.357	3	2028	55.19696662	50
27.357	3	2029	50.905786	50
27.357	3	2030	46.61917402	50
27.357	3	2031	42.38188041	50
27.357	3	2032	38.23726469	50
27.357	3	2033	34.22607445	50
27.357	3	2034	30.38531691	50
27.357	3	2035	26.74727759	50
27.357	3	2036	23.33873235	50
27.357	3	2037	20.18038906	50

time	condition CI	damage weight	performance weight	appearance weight	damage	performance	appearance
2019	87.457	0.43	0.43	0.14	87.8801	87.88012	84.85790
2020	84.802	0.43	0.43	0.14	84.8734	84.87345	84.36844
2021	81.868	0.43	0.43	0.14	82.2317	82.23179	79.63597
2022	78.665	0.43	0.43	0.14	79.4880	79.48802	73.61517
2023	75.212	0.43	0.43	0.14	75.5189	75.51891	73.33314

Appendix E

Matlab code

Function cost

```
% objective function-minimization of treatment cost
 function total_cost = costdoor(x)
disc_rate = 0;
maint_cost=xlsread('costdoor');
par_dim=134;
No=41;
total_cost = 0;
year=0;
for j=1:No
    for k=1:par_dim
        total_cost = total_cost +
maint_cost(k,j)*x(k,j,:);
    end
    m = mod(25,5);
    if m == 0
        year=year+1;
        total_cost = total_cost*(1+disc_rate)^(-
1*year);
    end
end
 end
```

Function condition

```
function condition_index = conditiondoor(x)
y=x;
par_dim=134;
No_par=1;
for i=1:No_par
    for j=1:par_dim
   [~,y2] = max(y(j,:,i));
if (37<=y2)&&(y2<=45)
y(j,:,i)=0;
y(j,35,i)=1;
y(j,26,i)=1;
y(j,17,i)=1;
y(j,8,i)=1;
```

```
y(j,y2,i)=1;
elseif (28<=y2)&&(y2<=36)
y(j,:,i)=0;
y(j,26,i)=1;
y(j,17,i)=1;
y(j,8,i)=1;
y(j,y2,i)=1;
elseif (19<=y2)&&(y2<=27)
y(j,:,i)=0;
y(j,17,i)=1;
y(j,8,i)=1;
y(j,y2,i)=1;
elseif (10<=y2)&&(y2<=18)
y(j,:,i)=0;
y(j,8,i)=1;
y(j,y2,i)=1;
elseif(1<=y2)&&(y2<=9)
y(j,:,i)=0;
y(j,y2,i)=1;
end
    end
end
x=y;
par_dim=134;
No=41;
CI_max=100;
maxseverity=100;
condition_index = 0;
CI = zeros(par_dim,No);
repearingweight= xlsread('repearingweightdoors');
severity= xlsread('severitydoors');
for j=1:No
    for k=1:par_dim
        if x(k,j)==1
            CI(k,j)=repearingweight(k,1)*severity(k,j);
        else
            CI(k,j)=0;
        end
        condition_index = condition_index + CI(k,j);

    end
end
condition_index = condition_index /5;
```

```
end
```

function global leader

```
Pgall=Xd;
n=size(D,1);
m=size(A_cur,1);
sig_A=[];
sig_S=[];
dist=[];
sum=[];
maxD1=max(D(:,1));
minD1=min(D(:,1));
maxD2=max(D(:,2));
minD2=min(D(:,2));
m1D=zeros(n,1);
m2D=zeros(n,1);
maxA_cur1=max(A_cur(:,1));
minA_cur1=min(A_cur(:,1));
maxA_cur2=max(A_cur(:,2));
minA_cur2=min(A_cur(:,2));
m1A_cur=zeros(m,1);
m2A_cur=zeros(m,1);
for f=1:n
    m1D(f)=(D(f,1)-minA_cur1)/(maxA_cur1-minA_cur1);
end
for f=1:n
    m2D(f)=(D(f,2)-minA_cur2)/(maxA_cur2-minA_cur2);
end
for f=1:n
    sig_A(f)=((m1D(f)^2)-
(m2D(f)^2))/((m1D(f)^2)+(m2D(f)^2));
end
for i=1:(size(A_cur,1))
    m1A_cur(i)=(A_cur(i,1)-minA_cur1)/(maxA_cur1-
minA_cur1);
end
for i=1:(size(A_cur,1))
    m2A_cur(i)=(A_cur(i,2)-minA_cur2)/(maxA_cur2-
minA_cur2);
end
for i=1:(size(A_cur,1))
```

```
   sig_S(i)=((m1A_cur(i)^2)-
(m2A_cur(i)^2))/((m1A_cur(i)^2)+(m2A_cur(i)^2));
end
sig_S=sig_S';
sig_A=sig_A';
distHu=zeros(m,n);
for i=1:m
    for j=1:n
        distHu(i,j)=sig_S(i)-sig_A(j);
    end
end
distHu=abs(distHu);
[gh,hg] = min(distHu');
gh = gh';
hg = hg';
NewCol=[];
for i=1:m
NewCol=[NewCol;i];
end
hg = [hg NewCol];
```

main matlab code

```
clear all
close all
tic;
No_par=100;
par_dim=1474;
No_Maint=45;
X=zeros(par_dim,5,No_par);
%1:repair d1
%2repair d2
%3:repair d3
%4:repair d1+d2
%5:repair d1+d3
%6repair d2+d3
%7repair d1+d2+d3
%0: do nothing
%8:full repleasment
arch_cap=100;
Tmax=100;
T_current = 1;
v=zeros(par_dim,No_Maint,No_par);
x_tmp=zeros(par_dim,No_Maint,No_par);
```

```
Y_prev=zeros(No_par,2);
A_cur=zeros(No_par,2);
%initial par
x=zeros(par_dim,No_Maint,No_par);
y2=randi(No_Maint,par_dim, No_par);
h = waitbar(0,'Initializing waitbar...');
for i=1:No_par
    for j=1:par_dim
            perc = i;
    waitbar(perc/100,h,sprintf('%d%%
initialization...',perc))
            x(j,y2(j,i),i)=1;
     end
end
close(h)
Pb=x;
%fitness eve
h = waitbar(0,'Initializing waitbar...');
for i=1:No_par
    perc = i;
    waitbar(perc/100,h,sprintf('%d%% fitness...',perc))
    Y_prev(i,2)=costpratc(x(1:par_dim,1:No_Maint,i));

Y_prev(i,1)=conditionpractic(x(1:par_dim,1:No_Maint,i))
;
    A_cur(i,2)= Y_prev(i,2);
    A_cur(i,1)= Y_prev(i,1);
end
close(h)
X_prev=x;
[C,Xc]=Pareto_PSO(A_cur,X_prev);
D=C;
Xd=Xc;
% % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% % % % % % %
% updata gloabel leader
% glbel leader calculation
%sig meth
Pgall=Xd;
n=size(D,1);
m=size(A_cur,1);
sig_A=[];
sig_S=[];
```

```
dist=[];
sum=[];
maxD1=max(D(:,1));
minD1=min(D(:,1));
maxD2=max(D(:,2));
minD2=min(D(:,2));
m1D=zeros(n,1);
m2D=zeros(n,1);
maxA_cur1=max(A_cur(:,1));
minA_cur1=min(A_cur(:,1));
maxA_cur2=max(A_cur(:,2));
minA_cur2=min(A_cur(:,2));
m1A_cur=zeros(m,1);
m2A_cur=zeros(m,1);
for f=1:n
    m1D(f)=(D(f,1)-minA_cur1)/(maxA_cur1-minA_cur1);
end
for f=1:n
    m2D(f)=(D(f,2)-minA_cur2)/(maxA_cur2-minA_cur2);
end
for f=1:n
    sig_A(f)=((m1D(f)^2)-
(m2D(f)^2))/((m1D(f)^2)+(m2D(f)^2));
end
for i=1:(size(A_cur,1))
    m1A_cur(i)=(A_cur(i,1)-minA_cur1)/(maxA_cur1-
minA_cur1);
end
for i=1:(size(A_cur,1))
    m2A_cur(i)=(A_cur(i,2)-minA_cur2)/(maxA_cur2-
minA_cur2);
end
for i=1:(size(A_cur,1))
    sig_S(i)=((m1A_cur(i)^2)-
(m2A_cur(i)^2))/((m1A_cur(i)^2)+(m2A_cur(i)^2));
end
sig_S=sig_S';
sig_A=sig_A';
distHu=zeros(m,n);
for i=1:m
    for j=1:n
        distHu(i,j)=sig_S(i)-sig_A(j);
    end
```

```
end
distHu=abs(distHu);
[gh,hg] = min(distHu');
gh = gh';
hg = hg';
NewCol=[];
for i=1:m
NewCol=[NewCol;i];
end
hg = [hg NewCol];
% % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% % % % % % % % % % % %
n_integer=5;
mut_rand=[];
gauss_norm=[];
unif_dist=[];
Mu=[];
Sd=[];
Data1 = [];
Data2 = [];
h = waitbar(0,'Initializing waitbar...');
for t= 1:Tmax
    perc = t;
    waitbar(perc/100,h,sprintf('%d%%
iteration...',perc))
for i=1:No_par
    for k=1:No_Maint
        for j=1:par_dim
            if i==hg(i,2)
               Pg=Pgall(:,:,hg(i,1));
            end
            Mu(j,k,i)= 0.5*(Pb(j,k,i)+Pg(j,k));
            Sd(j,k,i)= abs(Pb(j,k,i)-Pg(j,k));
            if Sd(j,k,i)~=0
                gauss_norm(j,k,i)
=(1/(Sd(j,k,i)*sqrt(2*pi)))*(exp((-1/2)*(((x(j,k,i)-
Mu(j,k,i))/Sd(j,k,i))^2)));
                unif_dist(j,k,i)= rand(1,1);
                if unif_dist(j,k,i) <0.5
                    x_tmp(j,k,i)=gauss_norm(j,k,i);
                else
                    x_tmp(j,k,i)=Pg(j,k);
                end
```

```
              else
                  x_tmp(j,k,i)=Pg(j,k);
              end
             v(j,k,i)=x_tmp(j,k,i)- X_prev(j,k,i);
         end
     end
end
% % % % % % % % % % % % % % % % % % % % % % % % % % % %
% % % % % % % % % % % % %
for i=1:No_par
    for j=1:par_dim
        max_velocity=max(v(j,:,i));
        countmax=0;
        for k=1:No_Maint
    if v(j,k,i)==max_velocity
        countmax=countmax+1;
        v_tmp(j,countmax,i)=k;
    end
    x(j,k,i)=0;
        end
        randnum=randi(countmax);
        indx=v_tmp(j,randnum,i);
        x(j,indx,i)=1;
    end
end
for i=1:No_par
    A_cur(i,2)=costpratc(x(1:par_dim,1:No_Maint,i));

A_cur(i,1)=conditionpractic(x(1:par_dim,1:No_Maint,i));
    X_prev=x;
    if
(((A_cur(i,2)<=Y_prev(i,2))&&(A_cur(i,1)<Y_prev(i,1)))|
|((A_cur(i,2)<Y_prev(i,2))&&(A_cur(i,1)<=Y_prev(i,1))))
        Y_prev(i,2)=A_cur(i,2); Y_prev(i,1)=A_cur(i,1);
        Pb(:,:,i)=x(:,:,i);
    else
         Y_prev(i,1)=Y_prev(i,1);
         Y_prev(i,2)=Y_prev(i,2);
         Pb(:,:,i)=Pb(:,:,i);
    end
end
% % % % % % % % % % % % % % % % % % % % % % % % % % % %
% % % % % % % % % % % % % % % % %
```

```
[C,Xc] = Pareto_PSO(A_cur,X_prev);
D=C;
Xd=Xc;
Pgall=Xd;
n=size(D,1);
m=size(A_cur,1);
sig_A=[];
sig_S=[];
dist=[];
sum=[];
maxD1=max(D(:,1));
minD1=min(D(:,1));
maxD2=max(D(:,2));
minD2=min(D(:,2));
m1D=zeros(n,1);
m2D=zeros(n,1);
maxA_cur1=max(A_cur(:,1));
minA_cur1=min(A_cur(:,1));
maxA_cur2=max(A_cur(:,2));
minA_cur2=min(A_cur(:,2));
m1A_cur=zeros(m,1);
m2A_cur=zeros(m,1);
for f=1:n
    m1D(f)=(D(f,1)-minA_cur1)/(maxA_cur1-minA_cur1);
end
for f=1:n
    m2D(f)=(D(f,2)-minA_cur2)/(maxA_cur2-minA_cur2);
end
for f=1:n
    sig_A(f)=((m1D(f)^2)-
(m2D(f)^2))/((m1D(f)^2)+(m2D(f)^2));
end
for i=1:(size(A_cur,1))
    m1A_cur(i)=(A_cur(i,1)-minA_cur1)/(maxA_cur1-
minA_cur1);
end
for i=1:(size(A_cur,1))
    m2A_cur(i)=(A_cur(i,2)-minA_cur2)/(maxA_cur2-
minA_cur2);
end
for i=1:(size(A_cur,1))
    sig_S(i)=((m1A_cur(i)^2)-
(m2A_cur(i)^2))/((m1A_cur(i)^2)+(m2A_cur(i)^2));
```

```
end
sig_S=sig_S';
sig_A=sig_A';
distHu=zeros(m,n);
for i=1:m
    for j=1:n
        distHu(i,j)=sig_S(i)-sig_A(j);
    end
end
distHu=abs(distHu);
[gh,hg] = min(distHu');
gh = gh';
hg = hg';
NewCol=[];
for i=1:m
NewCol=[NewCol;i];
end
hg = [hg NewCol];
D_prev=D;
mode=mod(t,5);
if mode==0
    F=figure(t);
plot(D(:,1),D(:,2),'ro','linewidth',1.5);
xlabel('f1(cost)');
ylabel('f2(CI)');
saveas(F,'FIG');
fn = num2str(t);
dlmwrite(fn,D,'delimiter', '\t');
movefile(fn,'MOPSOoutput');
end
end
close(h)
toc
```

Appendix F

Maintenance plane

Space id	Space type	Space area	System	MAINTENANCE PLAN
1	classroom	95	doors	0 0 5 0 0
2	classroom	98	doors	0 0 5 0 0
3	classroom	99	doors	5 0 0 0 0
4	classroom	100	doors	6 0 0 0 0
5	classroom	95	doors	0 0 5 0 0
6	office	8	doors	0 2 0 0 0
7	office	10	doors	0 0 0 3 0
8	office	8	doors	5 0 0 0 0
9	office	11	doors	0 4 0 0 0
10	office	8	doors	3 0 0 0 0
11	office	11	doors	0 0 0 0 0
12	office	12	doors	0 4 0 0 0
13	office	9	doors	0 5 0 0 0
14	office	11	doors	0 0 0 2 0
15	office	10	doors	0 0 0 2 0
16	office	10	doors	0 4 0 0 0
17	office	10	doors	0 0 0 1 0
18	office	10	doors	5 0 0 0 0
19	office	9	doors	5 0 0 0 0
20	office	8	doors	6 0 0 0 0
21	office	13	doors	7 0 0 0 0
22	office	13	doors	5 0 0 0 0
23	office	11	doors	0 5 0 0 0
24	office	12	doors	0 6 0 0 0
25	office	12	doors	0 0 0 5 0
26	office	9	doors	0 2 0 0 0
27	office	13	doors	6 0 0 0 0
28	office	8	doors	0 0 7 0 0
29	office	9	doors	3 0 0 0 0
30	office	13	doors	0 6 0 0 0
31	office	12	doors	3 0 0 0 0
32	office	10	doors	0 7 0 0 0

33	office	9	doors	0	0	6	0	0
34	office	8	doors	0	0	0	1	0
35	office	8	doors	0	5	0	0	0
36	office	12	doors	5	0	0	0	0
37	office	9	doors	0	0	0	1	0
38	office	13	doors	0	0	0	4	0
39	office	9	doors	0	7	0	0	0
40	office	9	doors	2	0	0	0	0
41	office	12	doors	1	0	0	0	0
42	office	8	doors	0	2	0	0	0
43	office	10	doors	0	5	0	0	0
44	office	12	doors	0	0	1	0	0
45	office	12	doors	1	0	0	0	0
46	office	9	doors	0	2	0	0	0
47	office	11	doors	0	0	5	0	0
48	office	10	doors	0	0	4	0	0
49	office	12	doors	0	4	0	0	0
50	office	9	doors	0	0	0	4	0
51	office	8	doors	2	0	0	0	0
52	office	10	doors	0	0	2	0	0
53	office	13	doors	5	0	0	0	0
54	office	11	doors	4	0	0	0	0
55	office	12	doors	0	0	5	0	0
56	office	12	doors	0	3	0	0	0
57	office	12	doors	0	0	4	0	0
58	office	11	doors	0	5	0	0	0
59	office	9	doors	0	0	2	0	0
60	office	13	doors	0	0	7	0	0
61	office	9	doors	0	0	0	3	0
62	office	10	doors	5	0	0	0	0
63	office	8	doors	0	0	5	0	0
64	office	13	doors	0	0	0	0	0
65	office	9	doors	4	0	0	0	0
66	office	8	doors	1	0	0	0	0
67	office	8	doors	7	0	0	0	0
68	office	8	doors	2	0	0	0	0
69	office	8	doors	0	0	0	0	0
70	office	8	doors	0	0	0	0	0

71	office	11	doors	4 0 0 0 0
72	office	11	doors	0 1 0 0 0
73	office	10	doors	0 0 7 0 0
74	office	9	doors	0 3 0 0 0
75	office	8	doors	0 7 0 0 0
76	office	11	doors	0 0 0 4 0
77	office	13	doors	0 0 3 0 0
78	office	13	doors	0 7 0 0 0
79	office	11	doors	0 0 0 1 0
80	office	13	doors	0 0 0 0 0
81	office	12	doors	6 0 0 0 0
82	office	10	doors	0 0 1 0 0
83	office	10	doors	0 0 4 0 0
84	office	9	doors	2 0 0 0 0
85	office	10	doors	0 0 0 0 0
86	office	13	doors	5 0 0 0 0
87	office	13	doors	7 0 0 0 0
88	office	11	doors	0 7 0 0 0
89	office	12	doors	5 0 0 0 0
90	office	13	doors	0 5 0 0 0
91	office	8	doors	0 0 0 1 0
92	office	8	doors	0 0 0 0 0
93	office	9	doors	0 0 0 1 0
94	office	10	doors	0 1 0 0 0
95	office	9	doors	0 7 0 0 0
96	office	12	doors	0 0 1 0 0
97	office	11	doors	0 0 7 0 0
98	office	10	doors	5 0 0 0 0
99	office	12	doors	0 2 0 0 0
100	office	12	doors	0 2 0 0 0
101	office	13	doors	0 0 4 0 0
102	office	9	doors	5 0 0 0 0
103	office	13	doors	0 0 1 0 0
104	office	11	doors	4 0 0 0 0
105	office	8	doors	0 0 0 3 0
106	office	10	doors	0 1 0 0 0
107	office	9	doors	0 2 0 0 0
108	lab	116	doors	5 0 0 0 0

109	lab	117	doors	0 4 0 0 0
110	lab	120	doors	1 0 0 0 0
111	lab	120	doors	7 0 0 0 0
112	lab	115	doors	0 5 0 0 0
113	lab	117	doors	2 0 0 0 0
114	lab	119	doors	0 1 0 0 0
115	lab	116	doors	0 3 0 0 0
116	lab	119	doors	2 0 0 0 0
117	lab	118	doors	0 5 0 0 0
118	lab	120	doors	0 2 0 0 0
119	lab	117	doors	2 0 0 0 0
120	lab	115	doors	0 4 0 0 0
121	lab	118	doors	0 4 0 0 0
122	lab	119	doors	6 0 0 0 0
123	lab	120	doors	0 0 0 4 0
124	lab	118	doors	1 0 0 0 0
125	Restrooms	24	doors	0 6 0 0 0
126	Restrooms	27	doors	0 0 0 1 0
127	Restrooms	24	doors	0 7 0 0 0
128	Restrooms	25	doors	6 0 0 0 0
129	Restrooms	24	doors	0 0 5 0 0
130	Restrooms	22	doors	7 0 0 0 0
131	Lunch rooms	645	doors	0 7 0 0 0
132	Lunch rooms	640	doors	0 5 0 0 0
133	Lobby	1000	doors	5 0 0 0 0
134	Auditoriums	120	doors	0 0 5 0 0

Space id	Space type	Space area	system	MAINTENANCE PLAN
1	classroom	95	walls	0 0 0 0 0
2	classroom	98	walls	0 6 0 0 0
3	classroom	99	walls	0 0 0 6 0
4	classroom	100	walls	0 0 0 6 0
5	classroom	95	walls	0 0 6 0 0
6	office	8	walls	0 0 0 0 0
7	office	10	walls	0 0 0 0 0
8	office	8	walls	0 0 6 0 0

9	office	11	walls	3 0 0 0 0
10	office	8	walls	0 0 0 4 0
11	office	11	walls	0 0 0 0 0
12	office	12	walls	6 0 0 0 0
13	office	9	walls	0 0 0 6 0
14	office	11	walls	0 0 0 6 0
15	office	10	walls	0 0 0 0 0
16	office	10	walls	6 0 0 0 0
17	office	10	walls	0 0 7 0 0
18	office	10	walls	0 0 0 0 0
19	office	9	walls	0 0 6 0 0
20	office	8	walls	0 6 0 0 0
21	office	13	walls	0 0 0 0 0
22	office	13	walls	0 0 0 0 0
23	office	11	walls	0 0 0 6 0
24	office	12	walls	0 0 0 0 0
25	office	12	walls	0 1 0 0 0
26	office	9	walls	0 0 0 0 0
27	office	13	walls	0 0 1 0 0
28	office	8	walls	0 0 0 0 0
29	office	9	walls	0 0 0 0 7
30	office	13	walls	0 0 0 0 0
31	office	12	walls	0 0 7 0 0
32	office	10	walls	0 0 0 0 0
33	office	9	walls	0 4 0 0 0
34	office	8	walls	0 0 0 0 0
35	office	8	walls	3 0 0 0 0
36	office	12	walls	4 0 0 0 0
37	office	9	walls	0 0 2 0 0
38	office	13	walls	7 0 0 0 0
39	office	9	walls	0 0 0 1 0
40	office	9	walls	0 5 0 0 0
41	office	12	walls	0 0 0 0 2
42	office	8	walls	0 0 0 1 0
43	office	10	walls	0 0 0 0 0
44	office	12	walls	0 0 0 0 0
45	office	12	walls	3 0 0 0 0
46	office	9	walls	0 0 0 1 0

47	office	11	walls	0	0	0	0	0
48	office	10	walls	0	0	3	0	0
49	office	12	walls	0	0	0	7	0
50	office	9	walls	0	0	7	0	0
51	office	8	walls	0	0	0	0	0
52	office	10	walls	6	0	0	0	0
53	office	13	walls	0	0	0	0	0
54	office	11	walls	0	0	0	6	0
55	office	12	walls	6	0	0	0	0
56	office	12	walls	0	0	0	0	0
57	office	12	walls	0	0	0	2	0
58	office	11	walls	0	0	0	0	0
59	office	9	walls	0	0	0	3	0
60	office	13	walls	5	0	0	0	0
61	office	9	walls	0	0	0	6	0
62	office	10	walls	0	0	0	6	0
63	office	8	walls	0	0	0	0	6
64	office	13	walls	0	4	0	0	0
65	office	9	walls	2	0	0	0	0
66	office	8	walls	0	0	0	7	0
67	office	8	walls	0	0	0	0	0
68	office	8	walls	4	0	0	0	0
69	office	8	walls	0	0	0	0	0
70	office	8	walls	0	0	0	3	0
71	office	11	walls	0	0	0	0	0
72	office	11	walls	0	0	0	0	0
73	office	10	walls	1	0	0	0	0
74	office	9	walls	5	0	0	0	0
75	office	8	walls	0	0	1	0	0
76	office	11	walls	0	0	0	0	3
77	office	13	walls	0	3	0	0	0
78	office	13	walls	0	7	0	0	0
79	office	11	walls	0	0	0	0	7
80	office	13	walls	1	0	0	0	0
81	office	12	walls	0	0	0	0	0
82	office	10	walls	0	0	0	1	0
83	office	10	walls	0	6	0	0	0
84	office	9	walls	0	0	0	6	0
85	office	10	walls	0	0	0	0	0

86	office	13	walls	2	0	0	0	0
87	office	13	walls	0	0	0	0	1
88	office	11	walls	6	0	0	0	0
89	office	12	walls	0	0	0	0	7
90	office	13	walls	0	5	0	0	0
91	office	8	walls	6	0	0	0	0
92	office	8	walls	0	0	0	0	0
93	office	9	walls	0	2	0	0	0
94	office	10	walls	0	2	0	0	0
95	office	9	walls	0	4	0	0	0
96	office	12	walls	0	0	7	0	0
97	office	11	walls	0	0	5	0	0
98	office	10	walls	0	4	0	0	0
99	office	12	walls	0	0	0	0	0
100	office	12	walls	0	0	0	2	0
101	office	13	walls	0	2	0	0	0
102	office	9	walls	0	0	6	0	0
103	office	13	walls	0	3	0	0	0
104	office	11	walls	0	0	0	3	0
105	office	8	walls	0	0	1	0	0
106	office	10	walls	0	0	3	0	0
107	office	9	walls	6	0	0	0	0
108	lab	116	walls	0	0	0	3	0
109	lab	117	walls	0	0	2	0	0
110	lab	120	walls	0	0	0	4	0
111	lab	120	walls	0	0	3	0	0
112	lab	115	walls	4	0	0	0	0
113	lab	117	walls	4	0	0	0	0
114	lab	119	walls	0	4	0	0	0
115	lab	116	walls	0	0	0	0	0
116	lab	119	walls	0	6	0	0	0
117	lab	118	walls	0	0	0	0	0
118	lab	120	walls	0	0	0	0	0
119	lab	117	walls	0	7	0	0	0
120	lab	115	walls	0	4	0	0	0
121	lab	118	walls	0	0	0	0	0
122	lab	119	walls	0	7	0	0	0
123	lab	120	walls	0	7	0	0	0
124	lab	118	walls	0	0	4	0	0

125	Restrooms	24	walls	0 0 0 4 0
126	Restrooms	27	walls	6 0 0 0 0
127	Restrooms	24	walls	0 5 0 0 0
128	Restrooms	25	walls	1 0 0 0 0
129	Restrooms	24	walls	0 3 0 0 0
130	Restrooms	22	walls	0 3 0 0 0
131	Lunch rooms	645	walls	0 6 0 0 0
132	Lunch rooms	640	walls	0 0 0 0 0
133	Lobby	1000	walls	0 0 0 6 0
134	Auditoriums	120	walls	6 0 0 0 0

Space id	Space type	Space area	COMPONANT FAMILY	MAINTENANCE PLAN
1	classroom	95	floors	6 0 0 0 0
2	classroom	98	floors	6 0 0 0 0
3	classroom	99	floors	0 0 0 0 0
4	classroom	100	floors	0 0 0 0 0
5	classroom	95	floors	0 0 0 0 0
6	office	8	floors	0 6 0 0 0
7	office	10	floors	4 0 0 0 0
8	office	8	floors	0 0 0 0 0
9	office	11	floors	1 0 0 0 0
10	office	8	floors	0 0 0 6 0
11	office	11	floors	0 0 0 0 0
12	office	12	floors	0 6 0 0 0
13	office	9	floors	0 0 0 0 0
14	office	11	floors	0 0 0 1 0
15	office	10	floors	3 0 0 0 0
16	office	10	floors	4 0 0 0 0
17	office	10	floors	0 0 0 0 0
18	office	10	floors	0 2 0 0 0
19	office	9	floors	0 0 2 0 0
20	office	8	floors	0 0 0 0 0
21	office	13	floors	0 3 0 0 0
22	office	13	floors	0 0 0 0 0
23	office	11	floors	0 6 0 0 0

24	office	12	floors	7 0 0 0 0
25	office	12	floors	0 2 0 0 0
26	office	9	floors	0 6 0 0 0
27	office	13	floors	1 0 0 0 0
28	office	8	floors	0 0 0 0 0
29	office	9	floors	0 6 0 0 0
30	office	13	floors	0 0 0 0 0
31	office	12	floors	0 4 0 0 0
32	office	10	floors	0 6 0 0 0
33	office	9	floors	0 0 4 0 0
34	office	8	floors	1 0 0 0 0
35	office	8	floors	0 0 0 0 0
36	office	12	floors	2 0 0 0 0
37	office	9	floors	0 5 0 0 0
38	office	13	floors	0 0 1 0 0
39	office	9	floors	5 0 0 0 0
40	office	9	floors	2 0 0 0 0
41	office	12	floors	0 0 0 0 0
42	office	8	floors	0 0 0 6 0
43	office	10	floors	2 0 0 0 0
44	office	12	floors	0 0 3 0 0
45	office	12	floors	0 0 6 0 0
46	office	9	floors	0 0 0 0 0
47	office	11	floors	0 0 2 0 0
48	office	10	floors	0 7 0 0 0
49	office	12	floors	1 0 0 0 0
50	office	9	floors	0 0 0 3 0
51	office	8	floors	0 0 2 0 0
52	office	10	floors	0 0 5 0 0
53	office	13	floors	0 2 0 0 0
54	office	11	floors	0 0 0 0 0
55	office	12	floors	7 0 0 0 0
56	office	12	floors	0 0 0 0 0
57	office	12	floors	0 5 0 0 0
58	office	11	floors	1 0 0 0 0
59	office	9	floors	0 7 0 0 0
60	office	13	floors	0 7 0 0 0
61	office	9	floors	4 0 0 0 0
62	office	10	floors	6 0 0 0 0

63	office	8	floors	0	0	0	0	0
64	office	13	floors	4	0	0	0	0
65	office	9	floors	0	0	0	0	0
66	office	8	floors	0	0	3	0	0
67	office	8	floors	0	4	0	0	0
68	office	8	floors	0	0	0	0	0
69	office	8	floors	0	0	0	0	0
70	office	8	floors	0	0	0	0	0
71	office	11	floors	0	0	1	0	0
72	office	11	floors	0	4	0	0	0
73	office	10	floors	0	2	0	0	0
74	office	9	floors	0	0	7	0	0
75	office	8	floors	0	0	0	3	0
76	office	11	floors	0	3	0	0	0
77	office	13	floors	0	0	6	0	0
78	office	13	floors	0	0	5	0	0
79	office	11	floors	0	0	1	0	0
80	office	13	floors	0	0	6	0	0
81	office	12	floors	5	0	0	0	0
82	office	10	floors	0	0	0	0	0
83	office	10	floors	0	0	4	0	0
84	office	9	floors	0	5	0	0	0
85	office	10	floors	0	0	0	0	0
86	office	13	floors	0	0	1	0	0
87	office	13	floors	3	0	0	0	0
88	office	11	floors	0	0	0	0	0
89	office	12	floors	0	0	6	0	0
90	office	13	floors	0	0	0	5	0
91	office	8	floors	2	0	0	0	0
92	office	8	floors	6	0	0	0	0
93	office	9	floors	2	0	0	0	0
94	office	10	floors	1	0	0	0	0
95	office	9	floors	0	7	0	0	0
96	office	12	floors	0	6	0	0	0
97	office	11	floors	0	1	0	0	0
98	office	10	floors	3	0	0	0	0
99	office	12	floors	0	0	0	3	0
100	office	12	floors	0	3	0	0	0
101	office	13	floors	0	2	0	0	0

102	office	9	floors	0 0 0 5 0
103	office	13	floors	0 0 0 5 0
104	office	11	floors	0 0 6 0 0
105	office	8	floors	0 0 0 0 0
106	office	10	floors	3 0 0 0 0
107	office	9	floors	0 0 4 0 0
108	lab	116	floors	0 0 2 0 0
109	lab	117	floors	0 0 0 0 0
110	lab	120	floors	0 4 0 0 0
111	lab	120	floors	1 0 0 0 0
112	lab	115	floors	0 0 0 0 0
113	lab	117	floors	0 0 0 0 0
114	lab	119	floors	0 3 0 0 0
115	lab	116	floors	0 5 0 0 0
116	lab	119	floors	0 7 0 0 0
117	lab	118	floors	0 6 0 0 0
118	lab	120	floors	0 0 4 0 0
119	lab	117	floors	0 5 0 0 0
120	lab	115	floors	0 0 0 1 0
121	lab	118	floors	0 0 0 2 0
122	lab	119	floors	0 0 0 1 0
123	lab	120	floors	0 0 1 0 0
124	lab	118	floors	0 0 2 0 0
125	Restrooms	24	floors	0 0 0 7 0
126	Restrooms	27	floors	0 0 1 0 0
127	Restrooms	24	floors	0 0 2 0 0
128	Restrooms	25	floors	6 0 0 0 0
129	Restrooms	24	floors	0 1 0 0 0
130	Restrooms	22	floors	6 0 0 0 0
131	Lunch rooms	645	floors	6 0 0 0 0
132	Lunch rooms	640	floors	6 0 0 0 0
133	Lobby	1000	floors	0 6 0 0 0
134	Auditoriums	120	floors	6 0 0 0 0

Space id	Space type	Space area	System	MAINTENANCE PLAN
1	classroom	95	celling	0 0 0 0 0
2	classroom	98	celling	0 0 1 0 0
3	classroom	99	celling	0 0 0 0 0
4	classroom	100	celling	0 3 0 0 0
5	classroom	95	celling	0 0 0 0 0
6	office	8	celling	0 0 0 0 0
7	office	10	celling	0 4 0 0 0
8	office	8	celling	0 0 0 0 0
9	office	11	celling	0 0 0 0 0
10	office	8	celling	0 0 0 0 0
11	office	11	celling	0 0 0 0 0
12	office	12	celling	0 0 0 0 0
13	office	9	celling	0 0 0 0 0
14	office	11	celling	6 0 0 0 0
15	office	10	celling	0 0 0 0 0
16	office	10	celling	0 0 0 0 0
17	office	10	celling	0 0 0 0 0
18	office	10	celling	0 0 0 0 0
19	office	9	celling	0 0 0 0 0
20	office	8	celling	6 0 0 0 0
21	office	13	celling	0 0 3 0 0
22	office	13	celling	0 0 0 0 0
23	office	11	celling	0 2 0 0 0
24	office	12	celling	0 0 0 0 0
25	office	12	celling	3 0 0 0 0
26	office	9	celling	0 5 0 0 0
27	office	13	celling	0 0 1 0 0
28	office	8	celling	0 0 1 0 0
29	office	9	celling	0 0 6 0 0
30	office	13	celling	0 0 0 1 0
31	office	12	celling	0 0 0 0 4
32	office	10	celling	0 6 0 0 0
33	office	9	celling	0 1 0 0 0
34	office	8	celling	0 2 0 0 0
35	office	8	celling	3 0 0 0 0

36	office	12	celling	0 0 0 0 0
37	office	9	celling	0 0 0 0 0
38	office	13	celling	0 4 0 0 0
39	office	9	celling	0 0 0 0 0
40	office	9	celling	0 0 0 7 0
41	office	12	celling	0 0 0 0 0
42	office	8	celling	0 0 0 0 0
43	office	10	celling	0 0 0 2 0
44	office	12	celling	0 0 0 0 2
45	office	12	celling	3 0 0 0 0
46	office	9	celling	0 0 0 0 1
47	office	11	celling	0 2 0 0 0
48	office	10	celling	0 0 4 0 0
49	office	12	celling	0 0 0 0 0
50	office	9	celling	0 0 0 5 0
51	office	8	celling	0 0 2 0 0
52	office	10	celling	6 0 0 0 0
53	office	13	celling	0 0 0 0 0
54	office	11	celling	0 0 0 1 0
55	office	12	celling	0 1 0 0 0
56	office	12	celling	0 4 0 0 0
57	office	12	celling	1 0 0 0 0
58	office	11	celling	0 0 0 0 1
59	office	9	celling	0 0 0 0 0
60	office	13	celling	4 0 0 0 0
61	office	9	celling	0 0 0 1 0
62	office	10	celling	0 0 0 0 0
63	office	8	celling	0 0 0 0 4
64	office	13	celling	0 0 0 0 4
65	office	9	celling	0 1 0 0 0
66	office	8	celling	0 6 0 0 0
67	office	8	celling	2 0 0 0 0
68	office	8	celling	0 0 0 0 5
69	office	8	celling	0 0 0 0 3
70	office	8	celling	0 0 0 5 0
71	office	11	celling	0 3 0 0 0
72	office	11	celling	0 6 0 0 0
73	office	10	celling	3 0 0 0 0

74	office	9	celling	0 0 0 3 0
75	office	8	celling	0 1 0 0 0
76	office	11	celling	0 0 7 0 0
77	office	13	celling	0 0 0 0 0
78	office	13	celling	0 0 0 0 0
79	office	11	celling	0 0 0 0 0
80	office	13	celling	0 4 0 0 0
81	office	12	celling	0 0 0 5 0
82	office	10	celling	0 0 0 0 0
83	office	10	celling	0 0 0 4 0
84	office	9	celling	0 0 1 0 0
85	office	10	celling	0 0 0 0 1
86	office	13	celling	0 0 0 1 0
87	office	13	celling	0 2 0 0 0
88	office	11	celling	0 0 0 0 0
89	office	12	celling	1 0 0 0 0
90	office	13	celling	0 0 6 0 0
91	office	8	celling	0 0 2 0 0
92	office	8	celling	0 0 0 0 0
93	office	9	celling	0 0 7 0 0
94	office	10	celling	0 0 5 0 0
95	office	9	celling	0 0 0 3 0
96	office	12	celling	0 7 0 0 0
97	office	11	celling	0 0 0 0 4
98	office	10	celling	0 0 4 0 0
99	office	12	celling	0 0 0 0 0
100	office	12	celling	0 0 0 6 0
101	office	13	celling	0 0 0 0 0
102	office	9	celling	0 0 5 0 0
103	office	13	celling	2 0 0 0 0
104	office	11	celling	0 1 0 0 0
105	office	8	celling	6 0 0 0 0
106	office	10	celling	0 0 0 0 2
107	office	9	celling	0 0 6 0 0
108	lab	116	celling	0 0 0 4 0
109	lab	117	celling	0 0 0 0 0
110	lab	120	celling	0 2 0 0 0
111	lab	120	celling	0 0 6 0 0

112	lab	115	celling	0 4 0 0 0
113	lab	117	celling	2 0 0 0 0
114	lab	119	celling	0 0 0 0 0
115	lab	116	celling	0 0 0 5 0
116	lab	119	celling	6 0 0 0 0
117	lab	118	celling	0 1 0 0 0
118	lab	120	celling	2 0 0 0 0
119	lab	117	celling	0 0 0 0 0
120	lab	115	celling	0 0 0 0 0
121	lab	118	celling	0 0 0 3 0
122	lab	119	celling	0 0 4 0 0
123	lab	120	celling	0 6 0 0 0
124	lab	118	celling	0 0 0 0 0
125	Restrooms	24	celling	0 0 0 7 0
126	Restrooms	27	celling	0 0 6 0 0
127	Restrooms	24	celling	0 0 0 0 0
128	Restrooms	25	celling	0 0 0 5 0
129	Restrooms	24	celling	0 0 0 0 6
130	Restrooms	22	celling	0 0 0 6 0
131	Lunch rooms	645	celling	0 6 0 0 0
132	Lunch rooms	640	celling	0 0 0 0 2
133	Lobby	1000	celling	0 0 0 6 0
134	Auditoriums	120	celling	0 0 0 6 0