Resilience-Based Asset Management Framework for Pavement Maintenance and Rehabilitation

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ABSTRACT

Resilience-Based Asset Management Framework for Pavement Maintenance and Rehabilitation

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Infrastructure systems play a pivotal role in developing the economy and public services, which positively affects the quality of life of the communities. Thus, it is of paramount importance to investigate the current infrastructure capacity, assess its capability to sustain the anticipated disruptions, then plan the necessary recovery strategies to reduce their detrimental significance and increase their resilience. The growing decline in roads condition has recently grasped the attention of numerous researchers and practitioners regarding road resiliency during its life-cycle. 62.6% of roads in Canada are in good condition, according to Canada Infrastructure Report (2016). Nevertheless, with current investment rates, significant road networks will suffer a decline in their condition and will be vulnerable to sudden failure (FCM 2016). On the other side, the current situation in the U.S is inferior, where roads are in poor condition, classified as grade D, and not to mention the insufficient investment required to maintain road networks (ASCE, 2017).

Accordingly, this research tackles pavement resilience from an asset management perspective where; it highlights the fact that infrastructure should maintain its resiliency during its life-cycle to maintain a minimum acceptable Level of Service (LOS). The main objective of this research is to develop a resilience-based asset management framework for pavement maintenance and rehabilitation (M&R). The proposed methodology involves a set of sequential steps as follows; 1) define infrastructure resilience, 2) investigate resilience-related indicators in the same dimension of resilience definition, 3) develop a resilience-based asset management model for M&R decisions, 4) optimize the attained M&R plan for short and long-term decisions, and 5) formulate a resilience index. First, resilience is defined based on a comprehensive review of the previous literature and targeting an integrated definition that combines both asset management and resilience concepts. Then, resilience-associated indicators are investigated based on the predefined resilience definition, and the different indicators are later classified and modeled for a pavement network.

The resilience-based asset management model is carried out through the development of five components; 1) a central database of asset inventory that includes numerous data that

would serve as input for the proposed model, 2) a pavement condition and level of service (LOS) assessment models that encompass the different effects of climatic conditions on pavement condition, surface, and structural conditions, and LOS, 3) regression modeling of the effect of Freeze-Thaw on pavement and investigation of flooding effect on both pavement surface and structural conditions, 4) financial and temporal models for recovery/intervention actions are formulated through computational models that account for the intervention costs and time, then link them to the later used optimization model, and 5) an optimization model to formulate the mathematical problem for the proposed resilience assessment approach and integrate the formerly-mentioned components. The utilized optimization model employs a single objective that relies on a combination of meta-heuristic rules. Genetic algorithms are utilized as an innovative idea that formulates the mathematical denotation for the proposed resilience definition. Principle Components Analysis (PCA) is used and manipulated as a novel method to establish resilience indicators' weights and compute the resilience index. A PCA framework is developed based on optimization model output to generate the required weights for the desired resilience index. This model offers dynamic resilience indicators' weights and, therefore, a dynamic resilience index. Resiliency is a dynamic feature for infrastructure systems, where it differs during their lifecycle with the change in maintenance and rehabilitation plans, systems retrofit, and the occurring disruptive events throughout their life-cycle.

The proposed model serves as an initial step toward providing more resilient municipal infrastructures. The model emphasizes that recovery plans should follow proactive measures to adapt to sudden or unforeseen events rather than just adopting a reactive approach, which deals with the sudden events after their occurrence. This pavement resilience assessment framework is also beneficial for asset management experts. M&R plans would not only target enhancing or restoring pavement condition or LOS but also incorporate the implementation of proper recovery strategies for both regular and extreme events into the M&R plan while taking the natural deterioration and aging effects into account. Two case studies were undertaken to demonstrate the effectiveness of the proposed methodology.

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To my dear mother, my inspiring father, and my little best friends Lama and Adam

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LIST OF NOMENCLATURE AND ABBREVIATIONS

AADT = Annual Average Daily Traffic

ANN = Artificial Neural Networks

BCA = Benefit-Cost Analysis

BCR = Benefit-Cost Ratio

CBR = California Bearing Ratio

DIIM = Dynamic Inoperability Input-output Model

DSS = Decision-Support System

GA = Genetic Algorithm

HMA = Hot-Mix Asphalt

IIM = Inoperability Input-output Model

IRI = International Roughness Index

KPI = Key Performance Indicators

LCC = Life-Cycle Costing

LOS = Level of Service

M&R = Maintenance and Rehabilitation

MCEER = Multidisciplinary Center for Earthquake Engineering Research

MLP = Multilayer Perceptron

PCA = Principal Components Analysis

PCI = Pavement Condition Index

PM = Preventative Maintenance

PMS = Pavement Management System

RI = Redundancy Index

RS = Resilience Index

SOM = Self-Organizing Map

SN = Structural Number

CHAPTER 1: INTRODUCTION

This chapter starts with a summary of the importance and challenges of maintaining the existing infrastructures. The resilience concept is introduced after that, followed by the motivation and problem statement for the current research. Then, the main research objectives are well defined. Then by the end, the research methodology and thesis structure are provided.

1.1. Research Background

In the past decade, several natural disasters have occurred worldwide, such as; the 2010 earthquake in Haiti that demolished Haiti's infrastructures and some important buildings and ascertained the necessity of crisis management for managing such disasters. Although preventive measures may reduce their intense effects, they can never eliminate them. Furthermore, keeping well-operated infrastructure systems is paramount to maintaining public safety, especially after severe hazards and disruption (Turnquist and Vugrin 2013). According to the Infrastructure Canada report (2016), the average age of the core infrastructure (e.g., bridges, roads, water, wastewater, transit, and cultural and recreational facilities) was about 14.7 years in 2013. As a result of aging, deterioration, severe weather conditions, and the effect of previous disruptions, infrastructure resilience becomes inferior. Therefore, introducing a strategic and managerial approach to these aging assets from an asset management perspective is vital to maintain their condition and public safety during their lifecycle.

Disruption may not only occur as a result of natural disasters, but it can also be a result of common causes of failures and manmade accidents resulting in unpredictable consequences; for instance, the 2012 blackout in India is an example of that and which is considered to be the largest blackout in the world's history. Traditional methods were used to overcome those disruptions by implementing various protection measures and increasing the physical protection of infrastructure. Nevertheless, the perspective has recently moved towards resiliency as an essential design characteristic in the early stages of infrastructure systems design. This approach is known as "Designing for Resilience". Accordingly, the current policy is directed toward increasing infrastructure resiliency, its capability to withstand and adapt to any disruption event, and later return to its normal state of operation (Baroud et al. 2015). As a result, resilience has dominated the civil infrastructure research trends and grasped the interests of many professional entities. Moreover, resilience has been one of the widely-used themes among many scientific conferences and a major topic under investigation by research projects sponsored by the National Science Foundation (NSF) (Bocchini et al., 2013).

1.2. Problem Statement and Motivation

An infrastructure is exposed to various multi-level disruption events, from aging's effects to disasters, that impede its function and subsequently cause disruption in the interdependent infrastructure networks. Accordingly, maintaining the existing infrastructure networks is essential to meet the required Level of Service (LOS) and keep them operational in a satisfactory state (Turnquist and Vugrin 2013). Moreover, sustaining these assets is necessary to increase their resistance to extreme and regular events (e.g., aging effects) and their capability to recover their performance within the desired time frame to meet the required LOS. Nevertheless, infrastructure networks are aging, and insufficient investment is being made to salvage what is lost due to loading and severe environmental conditions. As per Canada's Infrastructure 2016 report, the current physical condition rating of roads is "Acceptable". Nevertheless, the recent investment will diminish this condition unless prompt corrective measures are taken to increase the investment rate (FCM 2016). Besides, there is a growing need to introduce new assets to the existing infrastructure networks to satisfy the ever-increasing population that doubled during the period from 1960 to 2013 (Statistics Canada, 2015).

Integrating resilience in conjunction with the asset management concept in that context is necessary. This need arises from the growing burden on municipalities to maintain their assets in a satisfactory condition. Integrating the two concepts shall efficiently reduce maintenance and intervention plan costs to achieve the best budget allocation for infrastructure investments. Scholars also drew attention to the growing need to direct investments strategically to enhance a system's resilience in the face of the anticipated disruption. Such investment should involve a prioritization approach to satisfy limited budget and time constraints and achieve the overall effective resilience enhancement for the road network. Hence, it is essential to investigate the connection between resilience and other asset management concepts such as risk-based models. Resilience assessment models were limited in considering the effect of previous non-extreme disruption events on resilience. Previous models also, regarding pavement network, didn't introduce the impact of aging, deterioration, and extreme and non-extreme disruption events to assess pavement resilience. Though there are multiple optimization models for selecting near-optimal M&R plans for pavement networks, limited research has been undertaken to develop optimization models that aim to maximize pavement resiliency within the existing budgetary constraints.

1.3. Research Objectives

The main objective of this research is to build a Resilience-based Asset Management framework for pavements networks. This framework targets reducing the overall allocated budget for maintenance and rehabilitation, where M&R actions will target not only the anticipated non-extreme events but also the extreme events. Accordingly, this primary objective is subdivided into the following sub-objectives as follows:

1. Formulate a resilience definition with respect to the Asset Management concept and identify the leading resilience indicators.
2. Investigate pavement network resilience metrics in in accordance to the predefined leading resilience indicators.
3. Develop a Resilience-based Asset Management optimization model for pavement M&R intervention decisions.
4. Optimize the achieved M&R plan for short and long-term decisions.
5. Formulate a resilience index computational model based on the proposed resilience definition and methodology.

1.4. Summary of Research Methodology

Chapter 2 comprises the research methodology. The following points summarize the methodology used in this research, as shown in Figure 1.1:

- Literature review and resilience definition: A comprehensive literature review on infrastructure resilience is performed, and an asset-based resilience definition is mined. Later, literature review on multiple areas such as pavement condition rating systems, pavement deterioration, principal components analysis, and optimization application on pavement networks. Finally, limitations of previous research are extracted, and resilience definition is introduced as the primary outcome of this phase.
- Development of a Resilience-based Asset Management framework and the associated models: The second phase is developing the main framework for resilience assessment for

pavement networks based on the proposed resilience definition. Main resilience indicators are identified, and each indicator's required computational models are developed. The main disruption scenarios are defined with respect to the pavement networks case studies. Recovery indicators were devised in the form of M&R intervention actions. The principal Components Analysis technique is introduced as a novel method to obtain indicators weights based on the available network data. The mathematical formulation for resilience indicators weights and Resilience Index is established.

- Implementation and validation of the resilience assessment framework: The final research phase is implementing the proposed model. The developed resilience indicators models are integrated into an optimization model, which serves the proposed resilience concept in this study. Then, the framework is applied to two case studies as a proof of concept. The main outcomes for this phase will be a resilience-based maintenance and rehabilitation plan and a resulting resilience index for pavement network corridors.

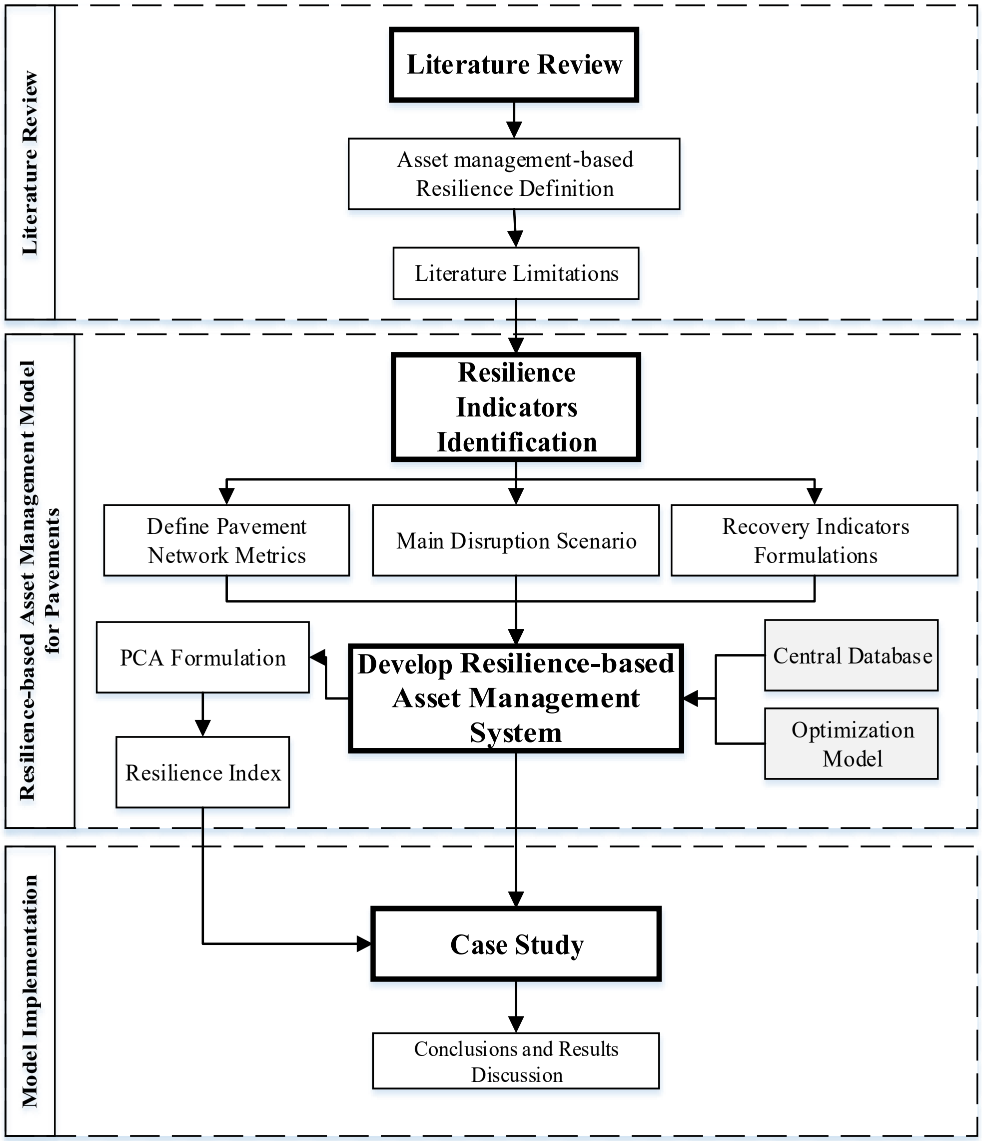


Figure 1.1: Schematic research methodology summary

1.5. Thesis Structure

This thesis is divided into six chapters. Chapter one briefly introduces infrastructures' importance and the problems existing infrastructures encounter. Next, the resilience concept is highlighted, followed by the motivation and problem foreseen behind this research. Then, the main research objectives are stated. Then to end, the proposed structure is provided. Chapter 2 provides an extensive state-of-the-art review of the existing resilience definitions from different approaches, professions, and disciplines, focusing on definitions related to infrastructure resilience. It also incorporates resilience assessment techniques in various engineering fields, pavement decision-making support systems, principal components analysis, application in this research, and optimization application in Pavement Management System (PMS). Finally, findings and limitations will be analyzed, and previous research gaps will be identified.

Chapter three demonstrates in detail the central general research methodology and discusses the mathematical formulation of each model in regard to pavement network. It involves five main sections: (1) identification of resilience-related indicators, (2) resilience indicators computational models and main resilience-based asset management model aggregation, (3) optimization model, and (4) PCA framework for indicators weight formulation. This framework is a general one which could be used for any infrastructure type while considering resilience indicators concerning the infrastructure type under study. Chapter three is followed by Chapter four which represents a pilot case study for the proposed model

Chapter five demonstrates the prominent case study figures, data collection, and the implementation of the proposed model in that case study, where model execution results and outcomes are shown and discussed thoroughly. Finally, Chapter 6 summarizes the proposed research work, covers the expected research contributions and limitations, and presents the opportunities for future work.

CHAPTER 2 – LITERATURE REVIEW

2.1. Introduction

This chapter aims to deliver an extensive literature review of the existing resilience definitions from different approaches, professions, and disciplines, focusing on definitions related to infrastructure resilience. The primary need for this review is to derive an asset management-based-resilience definition serving the research's problem statement and objectives. Also, this chapter demonstrates some of the resilience assessment techniques in different engineering fields. Furthermore, it presents an extensive review of pavement decision-making support systems. Moreover, this chapter illustrates the different pavement condition rating systems, deterioration and prediction models, and the adopted maintenance and rehabilitation strategies.

Furthermore, this chapter demonstrates a method developed here for pavement condition rating using principal components analysis. The main concept of PCA will be illustrated in detail, discussing its usage and manipulating it to meet the research's objectives. Finally, this chapter sheds light on optimization and its application in PMS. Figure 2.1 presents the methodology used to review the resilience definition and assessment literature.

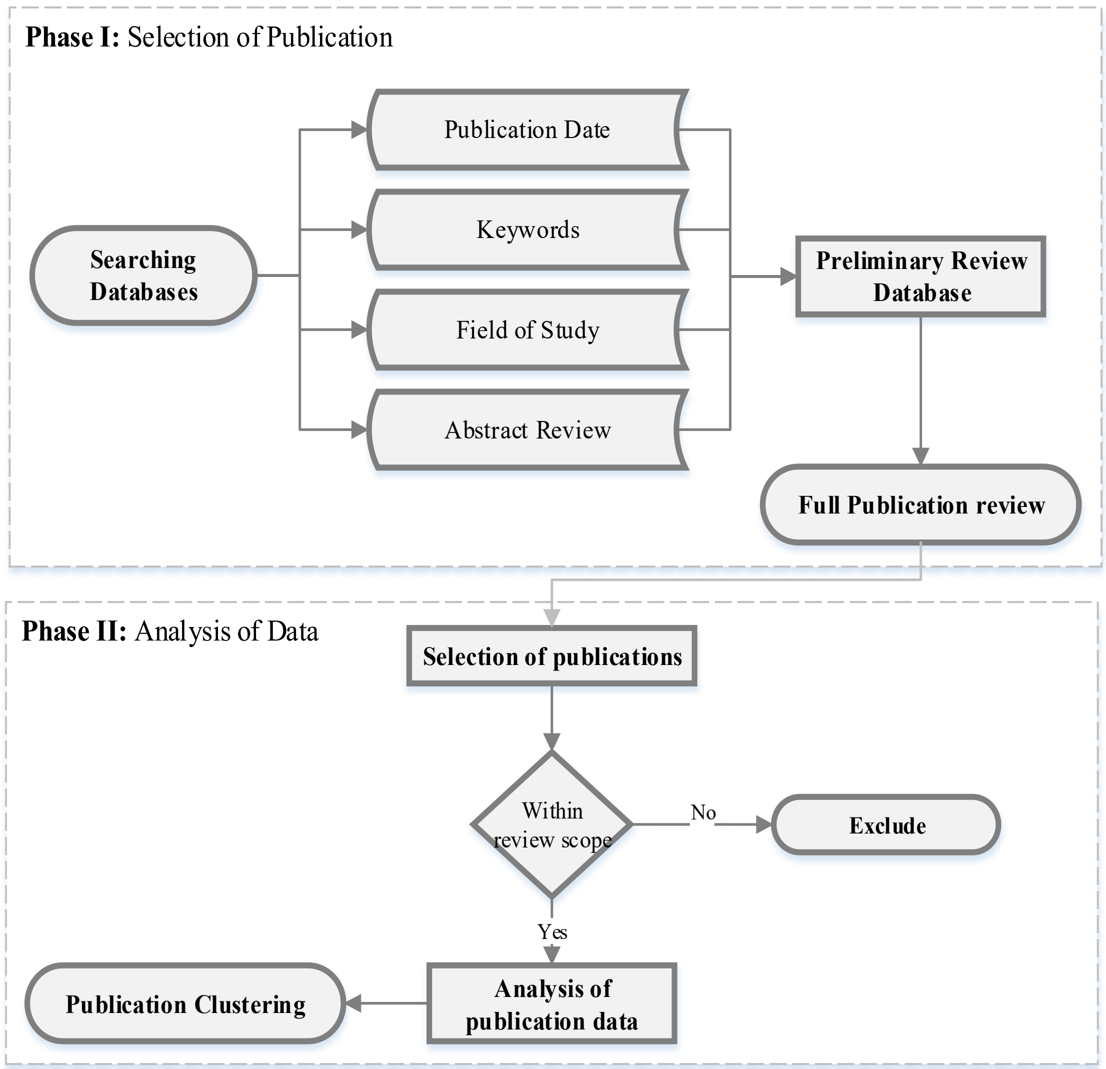


Figure 2.1: Schematic literature review methodology

2.2. Asset Management Approaches

Several approaches are employed when conducting asset management; performance-based and policy-based approaches are commonly used. Performance-based asset management can be further divided depending on the targeted performance measure, e.g., LOS, condition. On the other hand, the policy-based approach includes a life-cycle-costing-based approach that targets acquiring the best gains from the investment used in the process. In addition, numerous research work integrated risk management and asset management concepts and created risk-based asset management systems (Abu-Samra, 2014, Giglio et al., 2018, Federal Highway Association, 2022).

Limited studies focused on integrating resiliency into asset management. Simulation coupled with life cycle costing analysis was utilized to predict the necessary M&R plan for building facilities while considering both extreme and non-extreme events (Rasoulkhani et al., 2019, Izaddoost et al., 2021). Others incorporated risk analysis to assess road networks' resiliency to a seismic event. The main aim was to evaluate the resilience of road networks through risk analysis as part of road network asset management. Yet, the assessment was performed without considering other non-extreme events or deterioration impacts on the initial condition of the network. The focus was mainly on the recovery process to regain the initial condition of the road networks rather than considering the ability of a network to sustain the impact of the extreme event in parallel (Nicolosi et al., 2022). Liu, Y. and McNeil, 2020 investigated the connection between risk, resilience, and asset management concepts. The main reason was to enhance and strengthen the existing risk-based asset management process. Historical data and the asset management plans by 49 state departments of transportation in the U.S. were considered to reflect the effect of preparedness and recovery measures on the performance of road networks in case of flooding. Based on that, the chances of implementing resiliency and integrating it into the asset management plans were analyzed.

Resilience-based asset management approach plays a pivotal role and provides opportunities for M&R planning for road networks. That role is reflected through Intervention actions, which will target maintaining the regular deterioration and non-extreme events and enhance the pavement network for the anticipated extreme events.

2.3. Resilience Definition

There are many divergent interpretations of the conceptual definition of resilience across the different proficient disciplines. This divergence is devised from how the concept is applied and in which area of study it is used (Vugrin et al. 2010). As for this study, one of the goals is to reach a practical definition for the resilience of municipal infrastructure through investigating the current practices in defining infrastructure systems resiliency. While the concept of resilience is quite old, researchers adapted the definition to their fields to provided clarity. As for example, the ecologist C.S. Holling published one of the early research works describing resilience in their field of study. The definition was fundamentally focusing on resilience from a biophysical system-level perspective, where it was defined as "*a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables*" (Holling 1973) cited in (Vugrin et al. 2010) and (Zhou et al. 2010)).

Since Holling's definition, various conceptual definitions have been established in several categories, including but not limited to critical infrastructures, ecological systems, and economic resilience. Francis and Bekera stated that the existence of many definitions is an obstacle that prevents the presence of a universal understanding of resilience (Francis and Bekera 2014a). Nevertheless, according to how and in which discipline it is applied, resilience should still have its unique definition. Table 2.1 presents several definitions for resilience, mainly from critical infrastructures and disaster management perspectives. Two key observations were recognized from the reviewed definitions: (1) Resilience is defined via a set of parameters, and (2) Resilience is defined from a disaster management perspective. It is also apparent that these definitions have the consistency of resiliency wording, yet they are still localized to the research discipline of each study.

Table 2.1: Brief resilience definitions for infrastructure from the disaster management perspective

Resilience Definition	Author
"*The ability of systems, infrastructures, government, business, and citizenry to resist, absorb, recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance*"	(U.S. Department of Homeland Security Risk Steering Committee 2008 cited in (Vugrin et al. 2010))
"*A function indicating the capability to sustain a level of functionality, or performance, for a given building, bridge, lifeline network, or community, over a period defined as the control time" or the ability for an asset or system to sustain a minimum level of service or enactment for a specific time*"	(Cimellaro et al. 2010)
"*The ability of the mutual infrastructure systems to prevail the anticipated disruption and return back to normal state of operation*"	(Ouyang et al. 2012)
"*The ability of a system to efficiently recover lost function after disruption. It is defined by service loss, time of recovery and cost required to recover*"	(Gay and Sinha 2012)
"*The ability of a system or critical infrastructure to be restored to its original state after disruption or the post-event outcome of pre-event preparedness planning*"	(MacKenzie and Barker 2012)
"*Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or set of events) is the ability to reduce effectively both the magnitude and duration of the deviation from targeted system performance levels"*	(Turnquist and Vugrin 2013)
"*The ability to deliver a certain level of service even after the occurrence of an extreme event and to recover to the desired functionality as fast as possible*"	(Bocchini et al. 2013)
"*A time-dependent function to measure how a system is performing relative to the pre-active measures taken or the original required performance levels*"	(Baroud et al. 2015)
"*Definition a quality which reduces the vulnerability of an element, absorbs the effects of disruptive events, enhances the element's ability to respond and recover, and facilitates its adaptation to disruptive events similar to those encountered in the past*"	(Rehak et. Al. 2019)

The first set of parameters was defined by the Multidisciplinary Center for Extreme Events Research (MCEER) in New York, where resilience is characterized by four fundamental properties (R4); Robustness, Redundancy, Resourcefulness, and Rapidity. Robustness is defined as the system's ability to withstand a stress level resulting from a disruptive event without losing functionality. Redundancy is the capability of the system to substitute degraded system elements and maintain system functionality after disruption or loss of function. Resourcefulness is the system's ability to provide and manage resources in case of disruption. Finally, rapidity is the system's capacity to contain disruption and recover.

Gay and Sinha (2012) defined resilience as loss of performance, time for recovery, and the cost required to achieve recovery. Accordingly, a resilient system should withstand damage from a disruption event and efficiently recover the lost function within time and cost constraints. Several considerations were mentioned based on the MCEER definition. The first consideration was that most developments integrate both infrastructure and community resilience. Nevertheless, community resilience depends on infrastructure resilience, so applying the resilience concept to an isolated infrastructure system might be more beneficial to understanding an asset’s resiliency. Another crucial consideration is investigating the aging effect and system deterioration on the asset’s resilience by including the asset’s condition while assessing resilience. Another significant consideration from the MCEER definition is redundancy and resourcefulness correlation. Redundancy describes the alternative paths and resources available in case of disruption when the main resources are insufficient. Therefore, redundancy is strongly correlated to resourcefulness, where resourcefulness could provide means of redundancy, and both should be planned to provide a set of recovery possibilities (Cimellaro et al. 2010).

Another set of parameters used to define infrastructure's resilience includes absorptive, adaptive, and restorative capacity. The absorptive capacity deals with the system's ability to resist disruption. In contrast, adaptive capacity defines the system's capability to adapt to a disruption effect. In comparison, the restorative capacity is concerned with a fundamental management approach, which is restoring the infrastructure to its original state as quickly as possible while minimizing the restoration cost. According to the previous parameters, investments and funding planning should take place to satisfy those parameters and achieve the desired infrastructure's resilience against disruption (Turnquist and Vugrin 2013).

Several authors defined resilience based on their investigation. For example, according to Cimellaro's investigation of resilience definitions from the 90s, resilience was described as "*the capacity of a system or community to adapt and endure shocks and further recover*" or, according to the dictionary definition, resilience is defined as "*the aptitude to recuperate after shock or its resistance of shocks*". A community or a system needs preparedness measures and low vulnerability to obtain high resilience. Accordingly, Cimellero et al. (2010) offered three definitions to cover all resilience aspects; preparedness measures, mitigation, and recovery process. First, resilience is defined as *"A function indicating the capability to sustain a level of functionality, or performance, for a given building, bridge, lifeline network, or community, over a period defined as the control time"* or the ability of an asset or system to sustain a minimum level of service or enactment for a specific time. Second, recovery time is defined as the time required for a system to recover its performance or functionality to the same, close to, or higher than its original one. The third definition is the disaster-resilient community which is the community that can sustain extreme disruptive events with acceptable losses and recovers back using the necessary mitigation actions. The above definitions demonstrate disaster resilience based on the MCEER terminology described earlier.

However, Bocchini's study defined infrastructure resilience as "*the ability to deliver a certain level of service even after the occurrence of an extreme event and to recover to the desired functionality as fast as possible"* (Bocchini et al. 2013). Vugrin et al. (2010) proposed an event-associated resilience definition, stating that *"Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels"*. According to this definition, two measurable components are needed to evaluate the system's resilience. The first component is the Systemic Impact (SI), which reflects the difference between the targeted and actual system performance after a disruption. The other component is the total recovery effort, representing the effort and resources needed to recover after a disruption. The resilience concept should be an essential complementary element to enhance the traditional risk analysis approach, categorizing both risks with high-probability-low-impact and low-probability-high-impact in the same rank. The resilience concept adds means to the recovery process assessment and provides a more comprehensive risk analysis (Gay and Sinha 2012).

Based on the definitions mentioned above, resilience is associated with hazards and disruptions from catastrophic events. Nevertheless, it has been recognized that system resilience has not been previously noted as a life-cycle system criterion. In this context and to connect resilience to asset management conception, the author proposed a definition of asset resilience as "*The ability of an asset or a system to sustain a minimum level of service after average (regular and periodic) and extreme disruption events during its life-cycle within time and cost limitations"*. Three resilience aspects are highlighted in this definition. First is the asset capability to maintain a minimum level of service after a disruption. The disruption criteria form the second aspect. The third aspect includes the time and cost constraints required to achieve a minimum level of service. Figure 2.2 shows the different constraints that affect the asset's resilience.

To clarify the terminologies used in the definition, the following should be noted: 1) **Ability to sustain** is an expression that is equal to the absorptive capacity terminology mentioned and explained earlier by Turnquist and Vugrin (2013), 2) **Level of service** is "*the defined service quality for a particular activity or service area against which service performance may be measured"(InfraGuide 2003)*, 3) **Average disruption events** are the usual local events that affect the infrastructure's LOS during its life, these events are generally distinguished by a high probability of occurrence accompanied with a low impact, 4) **Extreme disruption events** are the global catastrophic events that could lead to significant infrastructure failure, these events are generally distinguished by low probability of occurrence accompanied with a high impact (e.g., Seismic), 5) **Time constraint** is the defined acceptable time for an infrastructure to recover to its original state after disruption, and 6) **Cost constraint** is the defined budget, including resources available, to achieve the recovery work after a disruption. Therefore, the proposed definition matches the strategy of QUÉBEC Infrastructure Plan 2021/2031. It aims to provide a superior level of service while maintaining a proper investment allocation for roadways to achieve maximum gains from the maintenance and rehabilitation plan.

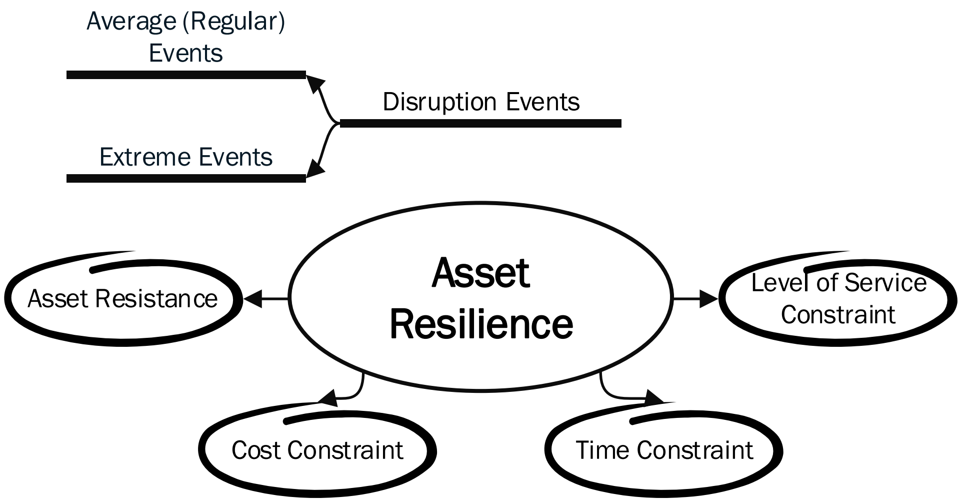


Figure 2.2: Resilience constraints of an asset

2.4. Resilience Assessment

Resilience had been assessed through different methodologies and bases, so it would be significant to demonstrate some of the used resilience assessment methods. For example, Zobel (2011) studied resilience by linking the recovery time to the initial impact of a disruptive event and studied the influence of the variability of the pre-event planning policies on the initial effect of a disruptive event and the recovery time. One concept for resilience application is applying it to an individual infrastructure system to better understand this isolated system's resilience. This concept is based on the fact that the recovery of one system shall improve the rest of the interconnected systems to a certain extent (Gay and Sinha 2012). Nevertheless, this can not be achieved because failures of one infrastructure system may cause failures in other interdependent systems.

The occurrence of a disruptive event does not imply the failure of specific infrastructure. Some systems may be vulnerable to certain types of disruption, while others may not. In addition, one system's characteristic may affect its ability to withstand a specific disruption event; thus, the resilience of most infrastructures is disruptive event specific. Moreover, assets' failure is known for its probabilistic nature. Furthermore, the relationship between the magnitude of a disruption event's effect and its probability of occurrence is said to be an inverse relation following a power law, as shown in Figure 2.3 (Gay and Sinha 2012).

The outcome of any disruption event may lead to the failure of some other infrastructure systems. From a sole infrastructure perspective, it is considered a local-level failure. Afterward, the next step would be propagating this failure to other infrastructure systems due to their interdependencies. Accordingly, different disruption scenarios should be investigated and analyzed to understand the reason behind each disruption and its consequences. Recently, an alternative approach for resilience analysis has been used to treat disruption as an inevitable event. Therefore resilience of infrastructure systems should be improved according to the anticipated disruption (Ouyang et al., 2012).

As previously shown in the data analysis section, different models and approaches were used to assess the infrastructure system's resilience. For example, MacKaenzie and Barker (2012) used Dynamic Inoperability Input-output Model (DIIM) to measure resilience, evaluate the initial impact of a disruptive event, and investigate the interdependency effect between infrastructure systems along with their recovery time. MCEER measures resilience based on the R4 framework, where it quantifies resilience through other four interconnected aspects: technical, organizational, social, and economical.

Many previous studies used the R4 approach. Nevertheless, they assumed that the original condition of a system is constant, and hence the resilience was statically measured. However, as the demand for public services grows, infrastructures' capacity increases and varies regularly.

Likewise, when any disruption occurs, the consequences are affected by previous disruptions. Thus, Ouyang et al. (2012) evaluated the resilience with respect to time and assumed there are inter-hazard interactions, although its effect can be implemented as the system's capacity increases. These two sides of resilience can not be neglected. Therefore, a dynamic-based approach to quantify resilience should be presented to correlate its relationship with the various anticipated disruption and time.

Gay and Sinha (2012) developed a tool capable of estimating the probability of a system being resilient against disruption. This tool was designed mainly for water distribution systems where; a resilient system implies the ability of a system to recover within a particular time and budget. Therefore, they developed a tool for assessing water distribution systems' resilience after disruption based on their ability to recover within time and cost constraints. The model consists of several inputs as follows:

1. Network parameters, properties, asset criticality ranking, and its dependency on the electric network.
2. Failure parameters, including the probability of failure and the available alternatives.
3. Recovery parameters include asset repair cost and time values, the estimated recovery function, and the time-cost constraints.

Since design characteristics of the water network affect its overall resilience, different design configurations, in the form of redundancies, were considered. The model output was in the form of network robustness and its recovery time and cost based on the functionality curve. Based on the failure modes calculations, each failure mode may be applied on the network level (Gay and Sinha 2012).

Another significant aspect of resilience is the “Recovery Process”, which is a complex process due to the considerable number of related matters. It relies on the available resources required to obtain the desired recovery goals and policies set by decision-makers. Besides, it is affected by geographical aspects and interdependent relations with systems and industries. For example, different water networks in diverse regions shall have different recovery strategies, paths, and qualities. Accordingly, when modeling a system’s recovery, it is crucial to determine whether it would be assumed as a single critical facility or analyzed as part of an entire community. Thus, Cimellaro et al. (2010) combined information from technical, organizational, seismology, social science, and economics into a distinctive function to provide an accurate methodology of risk perception. The function could capture disruption’s consequences, recovery, and preparedness measures’ results. The model was applied to two hospitals. It evaluated the economic losses based on their locations within a specific region based on non-linear dynamic analysis. The limiting states were chosen according to the design code.

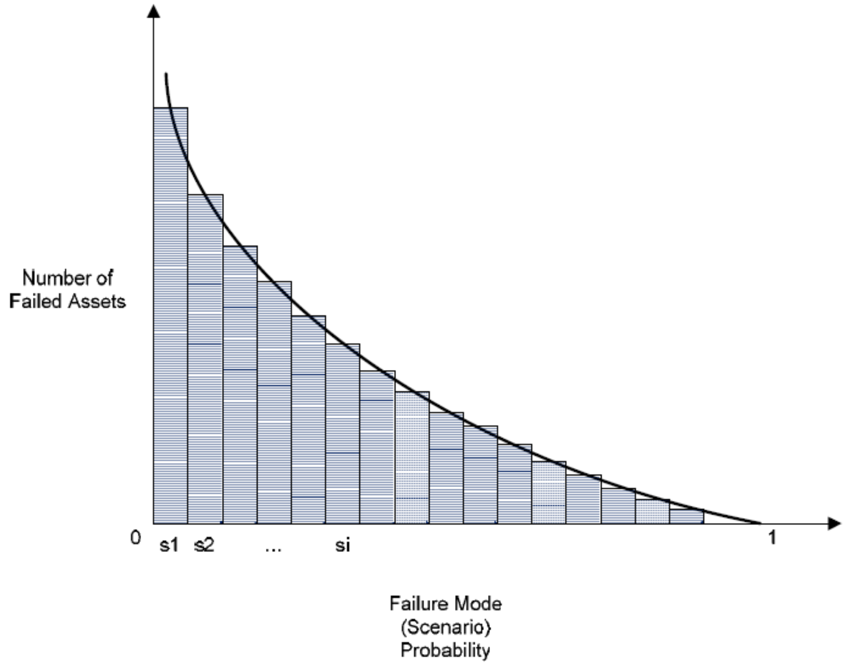


Figure 2.3: Relation between disruptive event effect and its probability of occurrence (Gay and Sinha, 2012)

Bocchini et al. (2013) developed a resilience assessment and analysis methodology throughout the infrastructure life-cycle while considering sustainability and resilience. Sustainability is connected to specific/predictable events and their impacts on the environment and community. At the same time, resilience addresses the effects of unpredictable extreme events, which have a low probability of occurrence. Since the approach was mainly directed towards investigating the impact of various events that could affect the infrastructure during its life-cycle, the risk analysis framework was mathematically developed as per the following equation:

$$I = \sum_{e \in E_r} P_e \, . I_e \; + \sum_{e \in E_s} P_e \, . I_e \qquad \text{Equation 2.1}$$

Where;

I is the expected life-cycle impact of the infrastructure on the community,

P_e and I_e are the probability and impact of event e,

E_s and E_r are the domain of events addressed by sustainability and resilience, respectively.

The previous concept was applied on a bridge where; two design options, Girder and Frame skeleton, were under investigation. Extensive data collection was performed to execute rough sustainability and resilience quantification. The main objective was to predict the implications of early decisions concerning the initial design, maintenance, and management of infrastructure over the infrastructure life cycle. The design decision varies where; one decision can lead to an enhancement of both sustainability and resilience. Nevertheless, other decisions could either lead to an enhancement in resiliency and reduction in sustainability or vice-versa. Life-cycle costing analysis and other techniques were used for sustainability analysis. The seismic event was considered for resilience assessment, as shown in Figures 2.4 and 2.5.

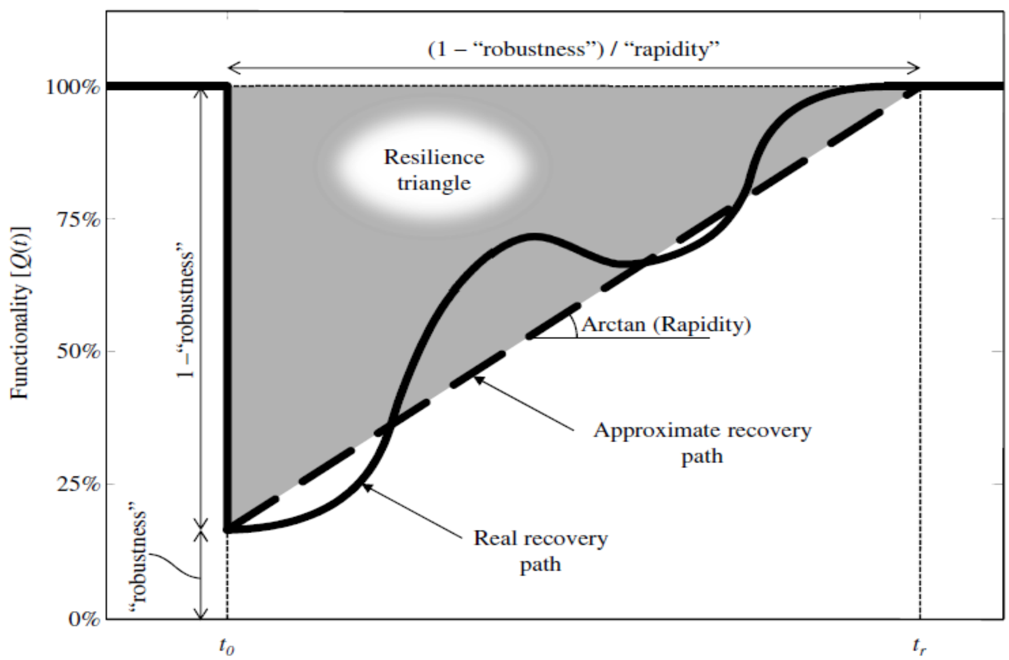


Figure 2.4: Resilience triangle and recovery path, t_0 is initial disruption time, t_r is complete network restoration (Bocchini et al., 2013)

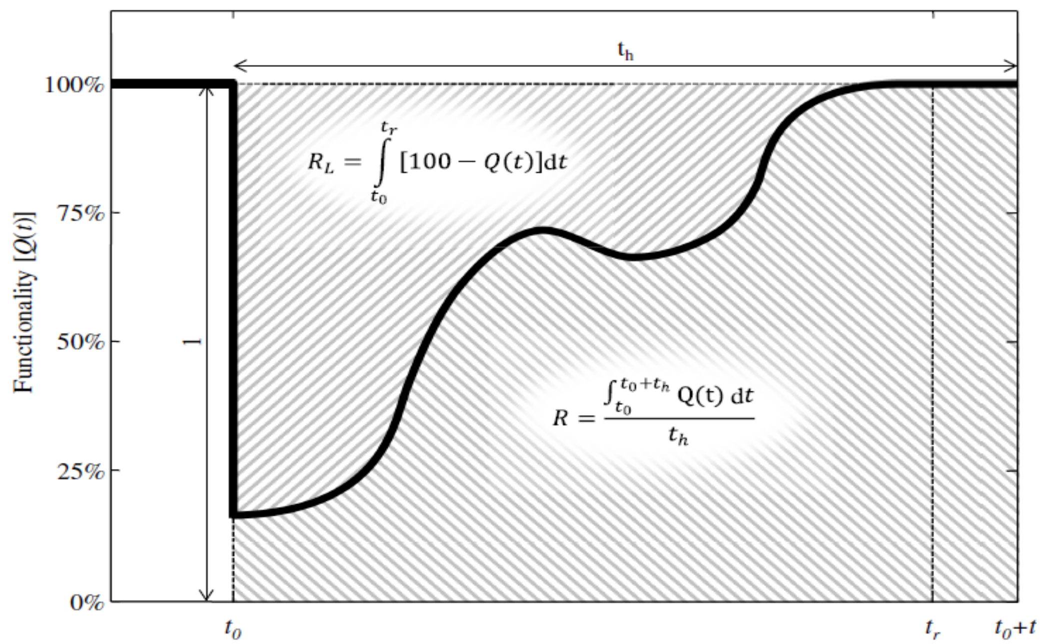


Figure 2.5: Resilience loss illustration diagram (Bocchini et al., 2013)

The calculation of resilience loss is a broadly used concept where a slight loss of resilience reflects high resiliency. This concept has been utilized and updated. Yang and Frangopol (2019) introduced lifetime resilience loss as an advanced approach when dealing with resilience loss due to extreme hazards lifetime resilience loss. Resilience is calculated as presented in Equation 2.2 based on Figure 2.6. The resilience loss in Equation 2.2 reflects a single hazard loss of resilience. Lifetime resilience loss can be calculated as shown in Equation 2.3

$$L_{R,i} = \int_{t_i}^{t_i+t_{rec}} Q(t)\, dt \qquad \text{Equation 2.2}$$

$$L_R = \sum_{t=1}^{N_h(t_L)} L_{R,i} \qquad \text{Equation 2.3}$$

Where;

$L_{R,i}$ is the resilience loss due to a single hazard i,

L_R is the lifetime resilience,

$Q(t)$ is the performance function,

t_{rec} is required recovery time,

$N_h(t_L)$ is the total hazards number up the calculation time.

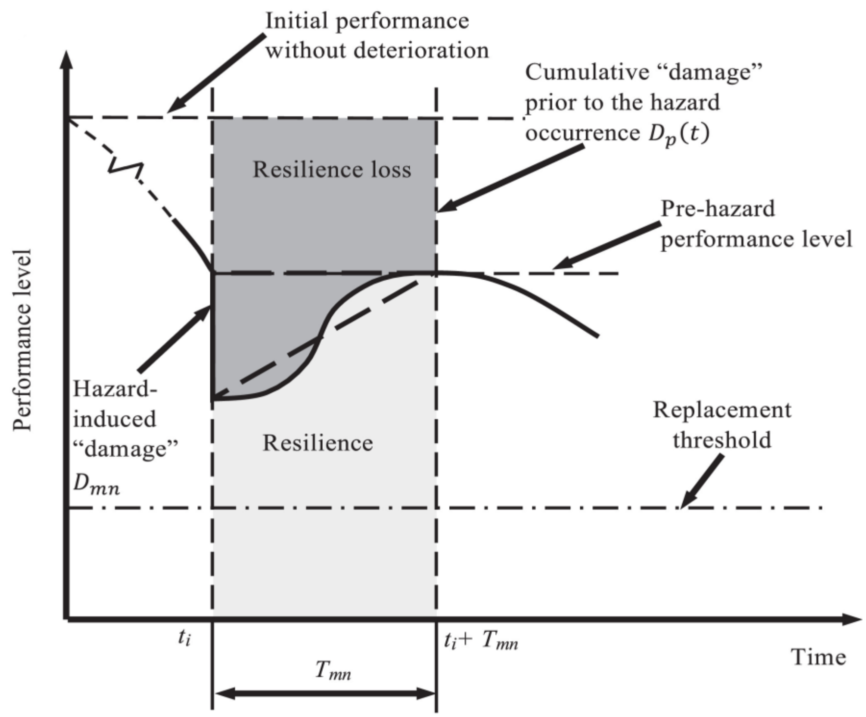


Figure 2.6: Resilience loss illustration diagram (Yang, and Frangopol, 2019)

This approach established two types of resilience losses: loss due to gradual natural deterioration and loss due to sudden breakdowns. The first time of resilience loss involves minimal repairs to keep the system working, while the second type involves significant replacement intervention action, as shown in Figure 2.7. This approach accounts for the natural deterioration of an infrastructure system throughout its life-cycle (Yang, and Frangopol, 2019).

Baroud et al. (2015) considered resilience a time-dependent function to measure a system's performance relative to the pre-active measures taken or the required initial performance levels. The approach was used to visualize the system's performance during and after a disruptive e^{j}

event, as presented in Figure 2.6, where $\boldsymbol{S_0}$ is the original system state, $\boldsymbol{S_d}$ is the disrupted system state, and $\boldsymbol{S_f}$ is the recovered system state after the recovery phase is finished. ***Φ (t)*** presents the system service function, which presents water-way goods and commodity flow along with the network. In Figure 2.6, it can be noticed that $\boldsymbol{S_f}$ is not the same as $\boldsymbol{S_0}$, where; the system may regain its functionality and improve its condition beyond the original condition to withstand any possible future disruption as a recovery process. Furthermore, the system improvement process may take place in different periods in the life cycle of an asset and is thus considered to be of a dynamic variation state even without disruption. This variation could result from many adverse factors such as; asset deterioration, aging effect, etc.

Baroud et al. (2015) have identified the system rehabilitation process as one factor that positively impacts the system performance over the life-cycle. Resilience is computed at time ***t*** as the ratio between system performance recovery at time *t* to the total performance loss caused by a specific disruption. The resilience (Я) can be mathematically calculated as per in the after-mentioned equation:

$$Я\ (t) = \text{Recovery}\ (t)\ /\ \text{Loss}\ (td) \qquad \text{Equation 2.4}$$

The model was combined with an interdependent behavior economic model, which modified the inoperability input-output model (IIM). The main reason for using this model is the accessibility and availability of the data that describe the interdependent effect and interconnected nature of infrastructure systems.

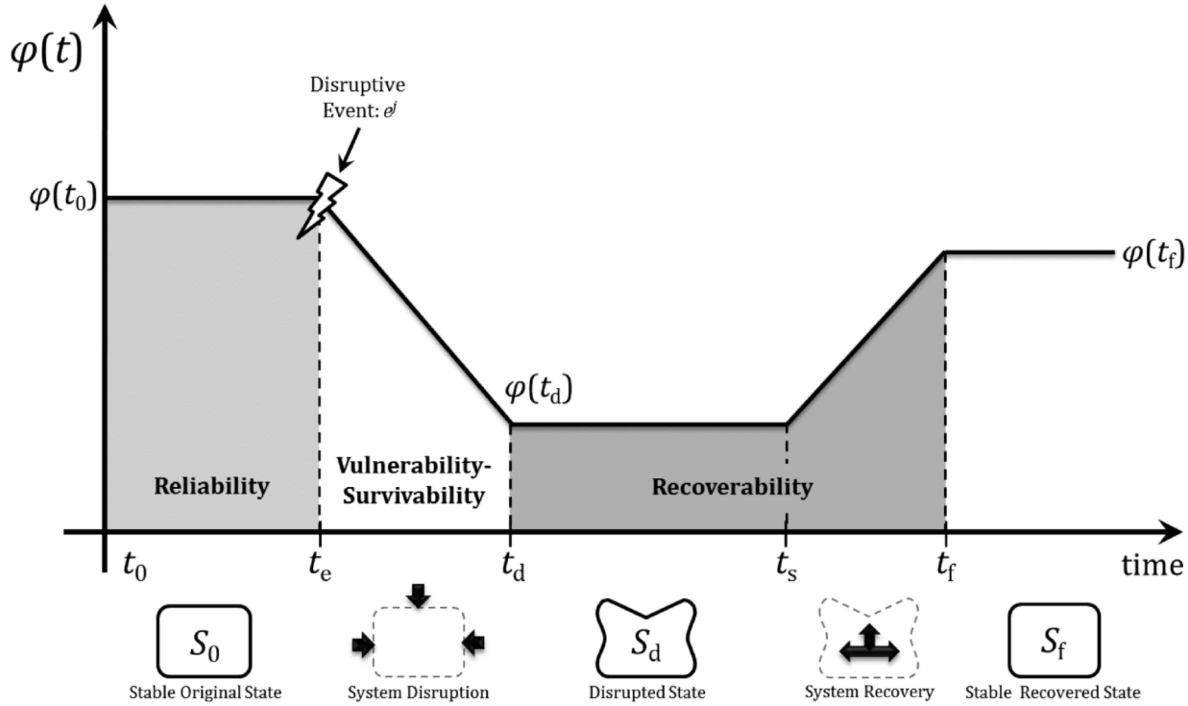


Figure 2.7: Schematic diagram for system functionality through its lifecycle under disruptive events effect (Baroud et al. 2015)

An important resilience aspect to shed light on is the associated resilience costs. Any extreme events cause different types of losses, divided into two categories: direct and indirect losses. Direct losses are related to the damage caused by the disaster, while indirect losses are related to interdependency (Cimellaro et al. 2010). Another two subcategories are derived from the types mentioned earlier: economic losses and casualties losses. Bocchinni et al. (2013) investigated the associated costs resulting from the occurrence of a seismic event as an extreme event where the associated costs were divided into direct and indirect costs. The direct costs were calculated using fragility analysis; they represent the costs resulting from the structural collapse, while the indirect costs addressed the loss of service costs and costs required to recover functionality.

Systems' inoperability due to disruption causes inherent network resilience costs. Thus, Baroud et al. (2015) divided the inherent costs into three types to evaluate any disruption. First is the cost resulting from the loss of service. Second is the cost required to regain the system's functionality. Last, the interdependent effect cost represents the loss in other industries and the systems relying on the disrupted system under investigation. The loss of service cost is measured as a function of the disruptive event severity period. The network restoration cost is the sum of restoration costs for all individual components of the infrastructure and depends on the recovery method used. Finally, integrating the resilience model and the modified IIM was created to quantify that interdependent effect.

Table 2.2 presents the different analysis methods used in each publication reviewed in the literature and the targeted field of each technique. The most frequently used methods for resilience assessment were based on mathematical models and simulation-based models. Those methods were mainly applied to power transmission grids, water distribution networks, and gas/oil pipeline cases, which are the main fields of study in infrastructure resilience investigation. In parallel to the previously mentioned methods, interdependency analysis occurred, especially with power transmission grid cases. Besides, decision-making analysis was one of the most used methods reflecting the goal/objective of resilience assessment, which opts at aiding the decision-making entities in taking verdicts towards more resilient infrastructure systems. The electrical power sector had the most significant publication portion, followed by the transportation and water distribution networks. This could be attributed to the high degree of interdependency and the effect of such infrastructure on other economic sectors and infrastructure.

Table 2.2 Modelling and analysis techniques for infrastructure resilience assessment

Modeling/Analysis technique	Publication	Field/Domain
Quantitative approach	(Vugrin et al. 2010; Baroud et al. 2015; Ip and Wang 2009; Alderson et al. 2015; Golara and Esmaeily 2016; Nan and Sansavini 2017; Tran et al. 2017; Murdock et al. 2018; Shin et al. 2018; Sun et. al. 2020; Dhulipala et. al. 2020)	Power transmission grid; Transportation network; Inland Waterway Network; gas/oil pipelines; Water distribution networks
Simulation	(Gay and Sinha 2012; Turnquist and Vugrin 2013; Shah, S. S. and Babiceanu 2015; Cuppens et al. 2012; Cimellaro et al. 2014; O'Rourke 2007; Nogal et al. 2017; Shakou et al. 2019)	Urban Wastewater networks; Water distribution networks; gas/oil pipelines;
Interdependency analysis	(MacKenzie and Barker 2012; Baroud et al. 2015; Shah, S. S. and Babiceanu 2015; Reed et al. 2009; Guidotti et al. 2016)	Power transmission grid; Inland Waterway Network; Telecommunications system
Mathematical model	(Ouyang et al. 2012; Ouyang and Dueñas-Osorio 2012; Shah, S. S. and Babiceanu 2015; Ikpong and Bagchi 2014; Cimellaro et al. 2014; Ouyang and Wang 2015)	Power transmission grid; Bridges; gas/oil pipelines;
Structural analysis	(Bocchini et al. 2013; Reed et al. 2009)	Design bridge layout options; Telecommunications system
Decision-making analysis	(Bocchini et al. 2013; Shah, J. et al. 2014; McDaniels et al. 2008; Creese et al. 2011; Brownjohn and Aktan 2013; Agarwal 2015; Lundberg and Johansson 2015; Mostafavi et al. 2017)	Design bridge layout options; Hospital; Oil storage and transfer depot; Bridges, Transportation network, Water network, Nuclear plant
Life-cycle cost analysis	(Bocchini et al. 2013)	Design bridge layout options;
Risk analysis	(Pedicini et al. 2014; Creese et al. 2011; Timashev 2011; Agarwal 2015)	Urban Wastewater utility management program; Oil storage and transfer depot; gas/oil pipelines

Modeling/Analysis technique	Publication	Field/Domain
Non-probabilistic judgmental characterization	(Chang et al. 2014)	City resilience
Comparative analysis	(Knudson and District, PE Tualatin Valley Water 2013)	Community resilience
Optimization	(Piratla and Ariaratnam 2013; Alderson et al. 2015; Fang and Sansavini 2019; Almoghathawi et. al. 2019)	Power transmission grid; Water distribution networks;
Hydraulic power concept analysis	(Saldarriaga et al. 2008)	Water distribution networks
Vulnerability analysis	(Francis and Bekera 2014b; Creese et al. 2011; Ikpong and Bagchi 2014)	Oil storage and transfer depot; Bridges
Statistical Process Control (SPC) methods	(Jung et al. 2013)	Water distribution networks
Media information/reports analysis	(Westerdahl 2014)	Nuclear reactor
Network theory model	(Lam and Tai 2012)	Transportation network;
Belief functions	(Attoh-Okine et al. 2009)	Transportation network; Water network
Disaster resilience of ‘‘Loss-Response’’ of location model	(Zhou et al. 2010)	Agricultural drought

2.5. Infrastructure Networks Redundancy

One of the leading factors taking vital importance in the resilience concept is redundancy. Therefore, a redundancy design should be implemented to create a resilient infrastructure. Nevertheless, few studies shed light on transportation network redundancy despite the extensive research on resilience. Additionally, limited research has established computational models capable of capturing the existing redundancy of transportation networks.

Two main criteria exist in transportation network redundancy: network capacity and network diversity. Network capacity represents the network-wide residual capacity considering travelers' behaviors in case of disruption events and their choices during congestions. In contrast, network diversity evaluates the existence of travel alternatives and modes in the network, their effectiveness for travelers, and the number of connections between two existing nodes. Utilizing travel diversity lacks the interconnection between the transportation demand and supply; accordingly, utilizing network diversity alone to evaluate network redundancy may not be sufficient in all cases. Furthermore, while the network spare capacity dimension is quantifiable, the travel alternative diversity is general and is mainly evaluated through network topology features. So, in general, utilizing network travel diversity solely is not sufficient to evaluate network redundancy regardless of the network configuration or the required enhancement plans. Nevertheless, these two redundancy measurement approaches can be integrated, providing two-dimensional network redundancy. A fair, unbiased network redundancy will be developed as a result (Xu et al., 2015).

The congestion effect and travelers' choice behavior are two critical characteristics of transportation systems. Network spare capacity is considered the second redundancy dimension to capture these characteristics adequately. Xu et al. (2015) evaluated network capacity by summating individual links' capacities between two nodes considering travel mode and choice. Several models were used to capture the required considerations and to create a multi-modal network spare capacity.

Others used a distance-based quantification method to measure rural roads' redundancy. This link redundancy measure was utilized to assess roads' performance (Chan et al., 2016, Shrestha et al., 2016). A link redundancy index (LRI) was developed to capture changes and detours that would appear in a rural road network in case of disruption. This index would reflect network performance relying mainly on rural road network links' length data. However, a network's performance and efficiency could also be reflected by considering each link's role as a rerouting option in case of network disruption. The combination of two redundancy measures could achieve flow-based redundancy, which reflects the amount of traffic redirected to a specific link in case of the disruption of another link. The combination would also attain impact-based redundancy, which demonstrates the impact of disruption of two links rather than one to capture the importance of the rerouting alternatives (Jenelius, 2010). Investigating redundancy in road networks would be beneficial for decision-makers to assess network routing performance during a disaster and determine a prioritization approach for maintenance and rehabilitation plans for road networks.

Redundancy was used to demonstrate an infrastructure's reliability and aid in forming response and mitigation plans in case of a disruptive event occurrence. Entropy theory was utilized in the transportation sector as an optimization aid to predict the demand in a transportation network between the available travel modes. It was also used to assess road network reliability based on the route entropy approach. In order to achieve this, entropy theory was utilized to create a redundancy index for road networks. Entropy theory was developed Shannon 1984 to measure the uncertainties in connecting channels and examine their performance. In a later investigation of the entropy theory, it was concluded that it demonstrates the number of degrees of freedom that exist in a network (El Rashidy, 2014). Accordingly, the general entropy measure is generally formulated as per Equation 2.5 and would later be manipulated to calculate the existing redundancy for links in a road network.

$$H(x) = \sum_{i=1}^{n} p_i \ln\left(\frac{1}{p_i}\right) \qquad \text{Equation 2.5}$$

Where;

$H(x)$ is the entropic measure of a system x,

n is the total number of system elements under consideration

p_i element parameter that identifies a specific characteristic for an element i.

It is essential to mention that entropy theory is widely utilized to capture an asset's properties and provide additional information related to that system. This was implemented in many studies targeting different infrastructure types like water and power grid networks (Hoshiya et al., 2002, Koc et al., 2013).

2.6. Pavement Decision-Making Support Systems

Planning maintenance and rehabilitation (M&R) strategies for pavement network over its life-cycle for achieving an optimized pavement condition is defined as Pavement Management System "PMS" (OCED, 2001). PMS is a well-recognized process by researchers and agencies. It is interpreted as an established tool and approach that provides decision-makers and top management related to highway authorities with effective and visible verdicts to maintain the desired pavement condition (AASHTO, 2001).

The term PMS was originally used in the late 60s' and early 70s'. It was demonstrated by the set of activities that formulate a systematic engineering approach capable of capturing construction and M&R pavement-related snags and maintaining pavement in a reliable, serviceable condition (Peterson, 1987). Since that period, growing interest in PMS, and more attention has been given to enhance that approach by many Canadian and U.S agencies (Chairul, 1991 cited in Abu-Samra, 2014). Hass et al. (1994) included all involved activities, from planning to M&R of pavement networks, as a broad pavement management approach for public works pavement programs.

Accordingly, and later on, different agencies and municipalities developed their own PMS research to match their needs. In developing countries in the 60s and 70s', roads were declared to be rapidly deteriorating, causing a breakdown in road networks due to the dramatic increase in traffic, the inadequate implementation of M&R strategies, and the lack of strategic planning in such countries. Another developed PMS targeting both project and network levels based on LCC for M&R of pavements was introduced by Sanjiv et al. (2004). Results showed 33% savings in cost over a study time of 20 years (Sanjiv et al., 2004). Jorn (2005) introduced the term "Minimum Cost Level", which reflects the optimized economic standpoint required to achieve the optimum service level, as shown in Figure 2.8 (Jorn, 2005 cited in Abu-Samra, 2014).

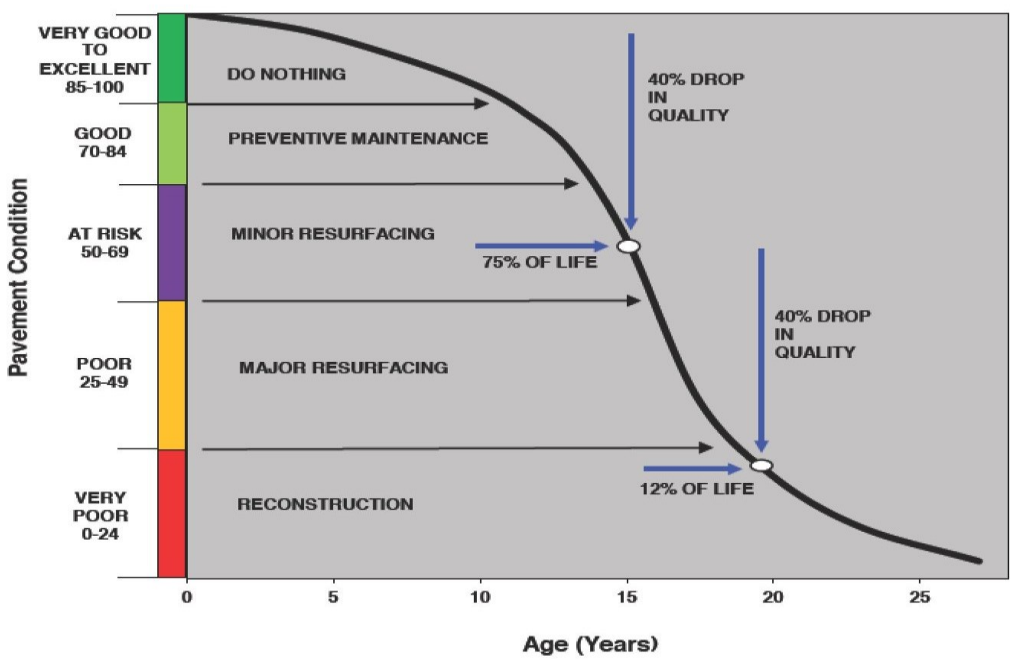


Figure 2.8: Pavement Deterioration curve (Riverside County Transportation Department, 2011)

Another example of PMS adaption is research by the Riverside County Transportation Department in 2011 that supports the existing management systems and priorities of M&R actions according to the available budget. A condition rating system was developed to transfer the numerical condition states to linguistic ones and to assess that system. A deterioration model was also developed and verified by studying the effect of PMS implementation on M&R actions selection, as shown in Figure 2.9 (Riverside County Transportation Department, 2011 cited in Abu-Samra, 2014).

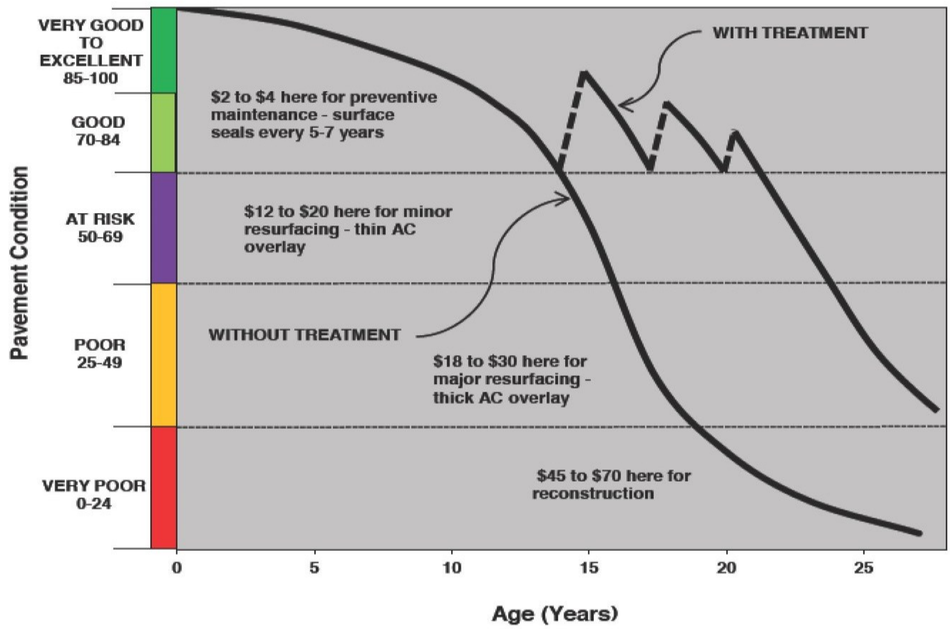


Figure 2.9: Effect of applying M&R on pavement deterioration (Riverside County Transportation Department, 2011)

2.7. Pavement Condition Rating Systems

Pavement condition rating systems were developed to compute a numerical figure representing the Pavement Condition Index (PCI), which would significantly aid in evaluating the performed M&R activities. In addition, precise PCI values would generate reliable numerical figures to present the actual pavement condition (Abu-Samra 2014). As a result, many systems were implemented to quantify pavement condition.

Building a pavement condition rating system is a well-studied topic by many researchers and organizations. For example, the New York State Department of Transportation (NYSDOT) utilized the various pavement elements that directly impact pavement condition. This was achieved through studying the associated deduct values curves for those elements. Furthermore, four elements were suggested and would be integrated to reflect pavement condition as follows (NYSDOT 2010 cited in Abu-Samra, 2014):

1. Surface distress
2. Ride quality (IRI)
3. Structural capacity
4. Friction

Hajj (2010) developed guidelines that would aid in selecting the intervention required for pavement M&R planning. These guidelines provide a long-term approach that integrates Benefit-cost analysis, the effect of improving different pavement KPIs, and the resulting performance growth in the pavement lifetime. In addition, various pavement stresses were identified to assess the existing pavement condition. Finally, these parameters were combined with the existing traffic and environmental conditions to provide an efficient M&R intervention plan (Hajj et al. 2010).

Lastly, Opus International Consultants (Canada) Limited (2012) developed another guideline to evaluate pavement condition. The manual includes definition, description, and detailed information regarding the different pavement surface defects. In addition, each defect was reviewed thoroughly, reflecting its effect on the pavement surface, criticality, and possible propagation through the pavement network. Finally, pavement surface condition assessment was introduced as a field inspection form that would aid in computing the PCI values (Opus International Consultants Limited, 2012 cited in Abu-Samra, 2014).

2.7.1. Deterioration prediction approaches

Pavement deterioration is "*a mathematical description of the expected values that a pavement attribute will take during a specified analysis period*" (Hudson et al. 1979 cited in (Abu-Samra 2014)). Deterioration models serve as the primary pavement functionality indicator. They also forecast the expected pavement condition during its life-cycle, considering different input factors such as aging, traffic, and environmental factors (OECD, 1987 cited in Abu-Samra, 2014).

Single and combined deterioration models can be utilized to evaluate the overall pavement condition. The difference between the two types of deterioration models is the associated number of pavement condition indicators. Single deterioration models are believed to give a better result regarding pavement condtion assessment. This would be reflected in the resulting M&R plan required to maintain the required KPIs for the pavement network. Therefore a better LOS would be achieved accompanied by an increase in pavement life-cycle. Based on this, it is worth mentioning that deterioration models play a significant role while developing PMS. An accurate well-developed deterioration model will eventually lead to a better cost-effective M&R intervention plan (Abu-Samra, 2014). Therefore, the following questions give a significant insight to aid decision-makers in developing a well-established deterioration model:

1. What type of distress or defect exists in the pavement network?
2. Where is each defect located in the pavement network?
3. How can this defect be treated to maintain an acceptable pavement condition and LOS)?
4. When should the treatment or intervention action take place for each corridor in the pavement network while minimizing the life-cycle costs?

2.7.2. Modeling methods for deterioration

Deterioration models reflect the pavement functionality through its life-cycle. Therefore, one of the main uses for those models is to estimate the pavement service life. For example, Figure 2.10 presents pavement deterioration mode with and without maintenance involvement. The remaining service life for pavement can be calculated through the deterioration model mentioned earlier and shown in the figure. Though there exist various classifications for pavement deterioration modeling methods, three major classes are recognized by many researchers as follows:

(a) Deterministic models
(b) Probabilistic models
(c) Bayesian models

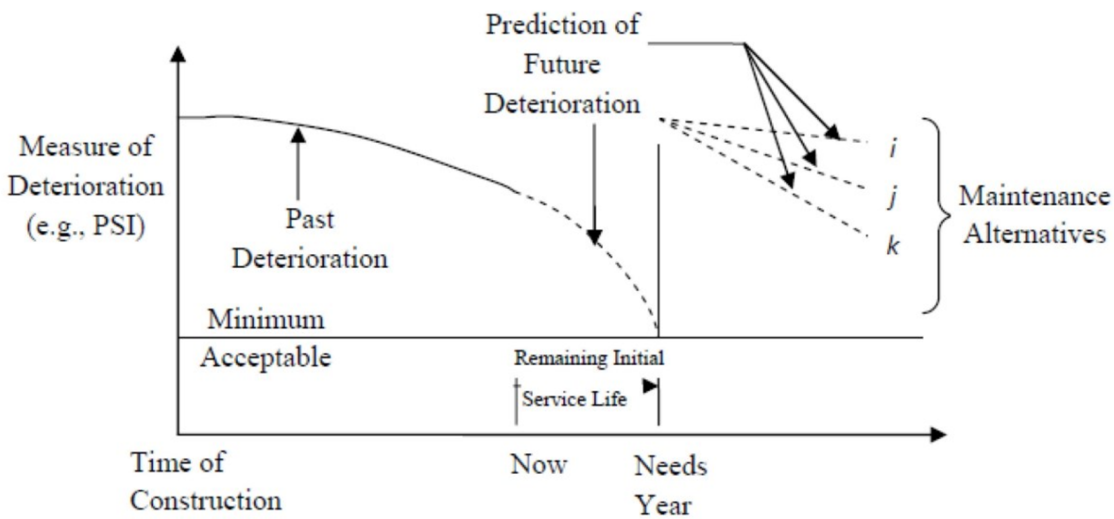


Figure 2.10: Deterioration model diagram indicating the remaining service life with and without M&R plan (FHWA, 2002b)

It is worth mentioning that data availability plays a pivotal role in choosing which type of model to use while addressing pavement condition. Another classification method for pavement deterioration models includes only deterministic and probabilistic approaches (Mahoney 1990 cited in Abu-Samra, 2014). Each type is summarized as follows:

1. Deterministic models are mathematical computational models that incorporate historical data to estimate the future pavement deterioration or value for any period of time (Durango, 2002).
2. Probabilistic models are established by designating various probabilities of occurrence for pavement condtion through its life-cycle (Durango, 2002).

Another method to distinguish pavement deterioration estimate methods is categorizing them into aggregate and disaggregate models. Aggregate models deal with the combined pavement condition indicators such as PCI. In comparison, disaggregate models deal with each defect solely to address its deterioration through the pavement life-cycle (Shahnazari et al. 2012; Abu-Samra 2014). Finally, Haas et al. (1994) incorporated traffic, environmental, and pavement structure to generate another classification for pavement deterioration modeling as follows:

1. Mechanistic models which rely mainly on traffic and environmental parameters.
2. Empirical models utilize pavement combined indicators such as PCI and connect between the PCI and other traffic (axle load criteria), environmental, and pavement structure (pavement layers features) parameters individually or combined.
3. Mechanistic-Empirical models which utilize regression equations that build the interaction between pavement defects and pavement performance indicators such as IRI.
4. Subjective models which rely on experts' input to create a probability matrix that aid in formulating the required deterioration forecasting model.

(a) Deterministic models

Deterministic models are created utilizing any of the empirical and mechanistic-empirical methods. Historical data availability is essential in order to correlate the resulting pavement deterioration model with the available real case data. Accordingly, this is established through a mathematical regression equation that fits the available data (Li, N. 1997 cited in Abu-Samra, 2014). In this context, developing pavement deterioration models based on a regression formula is a well-studied and investigated area. For instance, El-Assaly et al.(2002) investigated the deterioration rate in the LOS of pavement networks to evaluate pavement network performance and its expected service life in Alberta, Canada. Therefore, this study utilized IRI values as the main indicator for deterioration. Other researchers established deterioration models as part of a complete PMS. These deterioration models were used to assess the available design choices feasibility, the required M&R intervention actions, the required budget to be allocated, the LCC, and the different optimization plan alternatives through the pavement life-cycle. This approach and PMS were implemented by the Mississippi Department of Transportation (MDOT) (George (2000), cited in (Abu-Samra 2014)). The overall study procedures implemented in that approach could be summarized as follows:

1. Evaluate the different used deterioration models with respect to pavement type. Five different pavement types were included: flexible pavements, overlayed flexible pavements, jointed concrete pavements, continuously reinforced concrete pavements, and composite pavements.
2. Evaluate the difference between the forecasted and actual deterioration in each pavement type. Therefore, a feedback system was utilized to record the actual load values and calculate the substantial deterioration accordingly for each pavement type.
3. Based on the comparative analysis, Bayesian regression models demonstrated the most accurate models when generating pavement deterioration models.

Finally, some researchers compared the different available deterioration models used by various institutes in Portugal. The primary objective of this study is to analyze each performance modeling option with respect to its applicability to the highway networks in Portugal and later choose the most fitting model for this case (Ferreira et al., 2011).

(b) Probabilistic models

Probabilistic models have been developed to reflect the uncertainty in the deterioration process in pavement networks (Li, Z. 2005, Panthi 2009, AbuSamra, 2014). The Markov model has proven to be a valuable functional deterioration modeling tool and is widely utilized. Markov models gained their reputation because of their capability to demonstrate the uncertainty in the pavement deterioration process through its life-cycle. Markov models are classified into uniform and non-uniform models (Li Z. 1997). Uniform models deal with the various pavement condition indicators in a fixed approach through the pavement life-cycle.

In contrast, the latter incorporates the change of each pavement condition variable throughout pavement service life. Markov models consist of probability matrices that aid a time-dependent deterioration process while implementing the necessary M&R intervention plan (Panthi, 2009). Accordingly, the uncertainty is assumed to exist in the time required for the pavement to change from one condition to another or believed to exist in the pavement condition.

Markov models gained an outstanding reputation, being widely employed in many research practices. Markov chain models have been integrated into various PMS to evaluate the deterioration in the pavement. For instance, Adedimila et al. 2009 (cited in Abu-Samra, 2014), developed the following steps: historical data collection; create of probability transition matrices; develop of a suitable intervention action plan throughout the pavement life-cycle, and to conclude; implement cost-benefit analysis to demonstrate the gains between the traditional assessment methods and the proposed approach. It was concluded that introducing Markov-chain models had shown remarkable improvements in terms of BCA. Other researchers grasped the attention towards the pros of utilizing Markov-chain models on a network level to achieve an efficient M&R intervention plan.

Many researchers have successfully employed Markov-Chain models in PMS (Abaza and Ashur 1999). In addition, (Adedimila et al. 2009, cited in Abu-Samra, 2014) presented the pavement deterioration model as a part of their PMS. They developed the deterioration model based on historical pavement performance records to get the transition probability matrix and run for an optimum M&R action plan through the pavement service life. In addition, they carried out Benefit-Cost Analysis (BCA) to compare their results with the traditional results. It was evident that the impressive results showed an enormous difference from 57.2 to 466.9 BC ratio. (Haider et al., 2012) developed a Markov-chain model to evaluate the effectiveness of M&R strategies at a network-level PMS. They concluded that the advantages of using the Markov-chain model included the following:

1. Markov-chain models provide a conclusive concurrent approach to obtaining M&R intervention strategy along with the pavement deterioration.
2. They also provide early indicators of pavement performance and functionality throughout its life-cycle.
3. They deliver an extraordinary insight into the different M&R intervention plans, which will ultimately strengthen the decision-making process.

Other researchers utilized Markov-chain to forecast the pavement deterioration based on the consecutive computation of the transition matrices using ten-by-ten matrices. The forecasted deterioration models were generated to serve as a complete Decision Support System for pavement networks (Tjan and Pitaloka 2005; Surendrakumar et al. 2013, cited in Abu-Samra 2014). The resulting models showed a promising potential of Markov-chain models to forecast pavement deterioration with minimum deviation. As a result, M&R action could easily be traced to generate an efficient, cost-effective M&R plan and implement the required strategies to enhance pavement condition. Eventually, this would lead to a near-optimum, budget-friendly intervention plan.

Markov-chain modeling was further investigated to build a more comprehensive methodology to forecast pavement performance. This methodology considered two attributes to develop the probability matrices. The first attribute devised the probability matrices through pavement historical data, which is assumed to be available. The second attribute takes the unavailability of historical data, and thus, regression models were utilized to create the probability matrices based on the base data (Ortiz-Garca et al. 2006). Bayesian regression analyses were used to predict pavement deterioration by integrating expert opinion and the existing monitored data. Equation 2.6 summarizes the Bayesian hypothesis (Thomas, 1993, cited in Abu-Samra, 2014).

$$P(p|x) = \frac{P(x|p)\,.\,P(p)}{\sum|P(x|p)\,.\,P(p)|} \qquad \text{Equation 2.6}$$

Where;

- **P(x)** = distribution of variants over all possible fraction variants
- **P(p)** = prior distribution
- **P(x|p)** = sampling distribution
- **P(p|x)** = posterior distribution

(c) Artificial Intelligence (AI) models

Artificial Neural Networks (ANN) have been employed to predict the expected deterioration in pavement networks. Some researchers developed various ANN models capable of capturing pavement deterioration according to pavement type (Shekharan 2000). Others utilized ANN to create a pavement condition rating system and analyze the cracks existing in the pavement network (Yang et al., 2003, cited in Abu-Samra, 2014). Yang (2004), cited in (Abu-Samra 2014), had also integrated ANN with Markov-chain to provide a practical and reliable approach for pavement deterioration. Finally, ANN plays a crucial role in aiding decision-makers regarding M&R planning while assessing pavement deterioration and forecasting its future performance Suman and Sinha (2012).

2.7.3. Pavement maintenance and rehabilitation strategies

The purpose of this section is to provide background knowledge on the various M&R intervention practices used to improve pavement conditions. It also aims to incorporate various intervention strategies and investigate the associated effect on pavement condition and forecasted deterioration through PCI values. Furthermore, it intends to discuss multiple cases involving utilizing M&R plans to maximize PCI and the required LOS. Ultimately, this would support the decision-making process in creating efficient M&R intervention strategies while minimizing the associated costs through the pavement life-cycle.

Highway networks have been expanding exponentially to serve the population growth and the increasing economic demands. As a result, many public and private organizations developed various guidelines and standards to facilitate the implementation of M&R intervention approaches and clarify their future impact on pavement service life (Abu-Samra 2014). Nevertheless, with multiple M&R guidelines and manuals, pavement networks deteriorate rapidly, and cities cannot cope with that deterioration rate, mainly because of budgetary limitations. Therefore, the need for innovative M&R approaches is essential. This led many researchers to provide guidelines for M&R techniques implementation; for example, Wood et al. (2009) created the best management practices for HMA pavement M&R techniques implementation.

Many highway agencies and cities have widely used the preventive maintenance (PM) approach to cope with the rapidly deteriorated pavement networks. Surface crack techniques were adapted as budget-friendly techniques to decrease the rapid deterioration process in pavement networks—furthermore, these techniques aid in increasing pavement service life. Therefore, reconstruction or major rehabilitation techniques would take place later. Figure 2.11 presents analysis results for applying PM actions, and it is evident that PM aided in increasing pavement service life by approximately four years (Thomas et al., 2009).

In addition, Hicks et al. (2000) prepared a report explaining how to select the best PM strategy for flexible pavements (Hicks et al., 2000, cited in Abu-Samra, 2014). PM is addressed clearly in this report, covering such topics as the available PM strategies, the times and locations when these strategies should be employed, the PM cost efficiency, and the factors to consider when choosing an appropriate PM strategy for treating PM. Using PM strategies to improve pavement conditions and achieve a long-term lifecycle cost is one of the cornerstones of this report.

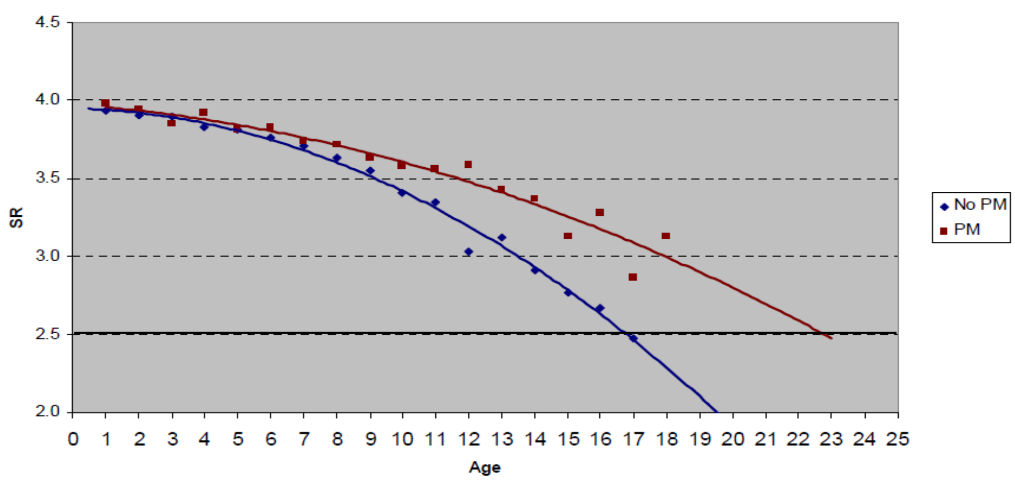


Figure 2.11: PM implementation effect on pavement service life (Thomas et al., 2009)

PM implementation has an extending effect on the pavement condition, as shown in Figure 2.12. Compared to utilizing no PM actions, it appears that an extension of the service life will be achieved with PM implementation along with better cost-effectiveness. There is also a substantial difference in the Net Present Value (NPV) between scenario (A) of applying PM and scenario (B) of not applying PM because the selection criteria were based on a “Decision tree” concept.

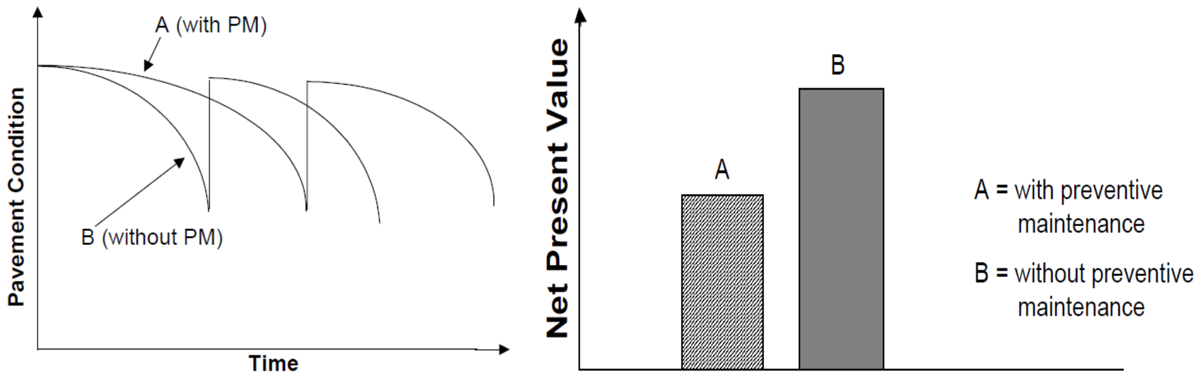


Figure 2.12: PM implementation cost effiency (FHWA, 2002b)

Decision trees use branches to indicate a particular PM strategy using various criteria. Each branch represents a specific set of conditions (for example, pavement type, defect type, traffic criteria) that ultimately lead to identifying a particular treatment., as the terminology suggests. In addition, Figure 2.13 illustrates a typical pavement deterioration curve while considering PM and no PM application scenarios. The difference between the two is that the cost per square meter for early PM implementation is much smaller than that for not implementing a PM plan. As a result, pavement life expectancy is better with PM, allowing highway agencies to own highways with longer service life (FHWA, 2002b)

In a nutshell, it is vital to use the appropriate maintenance and rehabilitation strategy at the right time during the pavement network life cycle to achieve a cost-effective operational pavement network. This approach is beneficial on many levels; for instance, early routine maintenance and intervention actions are four to six times more cost-effective than delaying intervention actions to take pavement later in pavement service life, as shown in Figure 2.13.

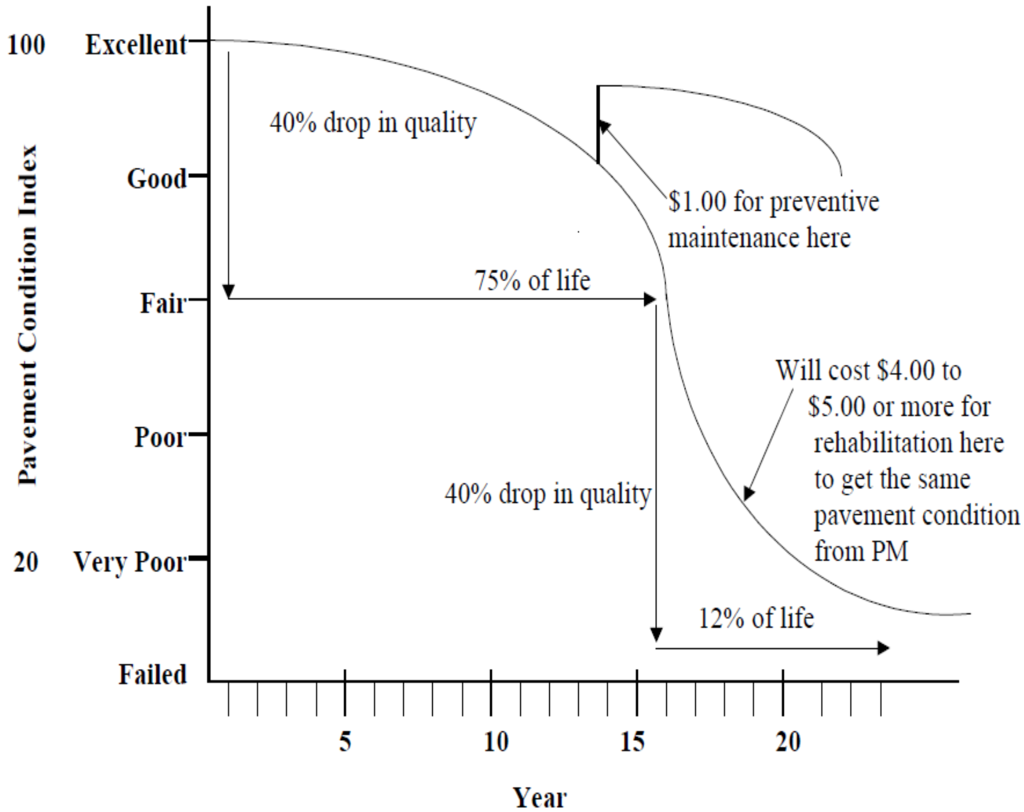


Figure 2.13: Early PM implementation effect on pavement service life and the associated costs (Hicks et al., 2000)

2.8. Flooded Pavements Deterioration

Pavement networks are subjected to extreme disruptive events during their life cycle, which vary from one network to another. Based on the geographic location of the pavement network, different disruptive events can take place and adversely affect pavement performance. Flooding is considered the most common extreme disruptive event that occurs in different regions across Canada (Climatedata.com, 2021). River flooding usually occurs due to intense rainfall or in the flooding season after snow melts during the spring in Canada. In contrast, coastal flooding is the result of severe storms and tsunamis. The existing pavement networks are not sufficiently designed to signify the impact of climate change and thus increase flood risk. Therefore, it is crucial to consider and investigate the effects of flooding on pavement networks to create a resilient pavement network by creating efficient maintenance and rehabilitation plans incorporating flooding impact. The flooding impact can be defined by the deterioration pattern and the deterioration type that occurs in pavement surface and structure, as shown in Figure 2.14. (Lu et al. 2020; Sultana et al. 2016; Lu et al. 2017).

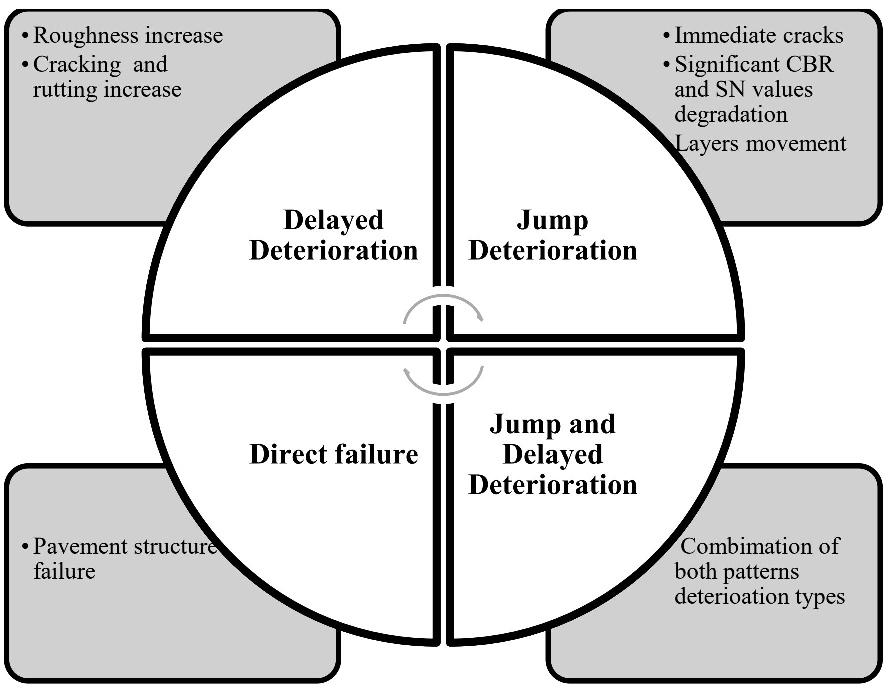


Figure 2.14: Pavement deterioration patterns and type due to flooding (Lu et al. 2020; Sultana et al. 2016; Lu et al. 2017).

Delayed deterioration implies that pavement deterioration occurs rapidly after a flood and not gradually with time. The CBR and SN values decrease can reach up to 50% of their value before flooding. Asphalt mixture aggregates segregation due to flooding is one of the significant deterioration results of pavement saturation during flooding, accelerating the overall pavement deterioration process after flooding.

The primary sources of pavement deterioration during and after flooding can be summarized as follows, the flood velocity force impacting the pavement structure and surface, the influence of flood depth and period of flooding, and pavement permeability to flooding water (Lu et al. 2020). The dry period has a crucial effect on the pavement deterioration trend in the long term, where the flooded pavement regains part of the lost strength during that period. Accordingly, the period to keep the flooded pavement corridors closed to traffic after a flood is as important as the rehabilitation actions taken to maintain pavement due to flooding (Sultana et al. 2016). Return period is one of the main criteria when designing pavement for flooding or studying pavement resilience regarding the flooding hazard. In Ontario, Canada, a return period ranging from 50 to 100 years is used when designing for flooding for freeways, while it goes from 25 to 50 years for rural and collector roads (fin.gov.on.ca, 2021). Nevertheless, and with climate change, those ranges may need to be revised.

Flooding was investigated for its effect on pavement IRI deterioration and thus producing post-hazards maintenance and recovery approach (Khan et al. 2014). Road network vulnerability was also investigated for the floods resulting from heavy precipitation. Performance of the transportation network in terms of average speed was the main target of that investigation to determine road vulnerability and its relationship with flood depth and speed reduction on flooded roads (Singh et al. 2018).

In the event of flooding, pavement condition should be adequately investigated to determine the significant damage and deterioration that occurred in either pavement surface or its structural components. A significant decline occurs in the flooded pavement network after flooding. Pavement structure components may suffer considerable damage after flooding without being detected based on surface condition assessment only. This shall create potential rapid failure in those components if not rehabilitated, probably after detection. On the other hand, during some flooding events, an entire pavement network could be wiped out, raising the question; whether building more resiliency and investing more resources to obtain a more resilient pavement network will be cost-effective in the long run. Sultana et al. 2014 studied the effect of flooding on the pavement by assessing pavement condition before and after a flooding event. Deflection and surface condition was the primary input for the assessment model. Surface condition and deflection data were obtained before and after flooding. It is important to note that the reduction in pavement condition after flooding is rapid and could reach up to 50% from its condition before the event or could reach a more significant reduction according to flooding intensity and pavement condition prior to the flooding event. Pavement surface condition does not reflect its structural condition after flooding, and if the necessary rehabilitation actions are not undertaken, a significant reduction in pavement service life will occur.

Helali et al. 2008 investigated the aftermath of both hurricanes Katrina and Rita and the significant damage and deterioration in pavement networks in the flooded areas. Pavement network condition before hurricanes was estimated, and structural analysis and surface condition assessment were performed. Pavement sections that were totally or partially flooded had higher deflection values than those that did not undergo flooding. Higher deflection values indicate significant damage and deterioration in pavement structural components (Shamsabadi et al. 2014). An initiative started investigating the decline in pavement performance throughout North America, known as the Long-Term Pavement Performance (LTTP) program. Twenty years of data were used to observe and predict pavement deterioration by utilizing regression analysis. This data includes pavement characteristics and the induced stresses in pavement layers, weather-related data like freezing index, precipitation, roughness measurements, traffic data, and maintenance-associated actions. This program formulated an equation to predict IRI deterioration in the flexible pavement under regular load and climatic conditions, as shown in Equation 2.7. One major limitation of this module is that it lacks o including the effect of extreme disruptive events on the pavement during its life cycle (Shamsabadi et al. 2014).

$$\ln(\Delta IRI + 1) = Age\left(4.50FI + 1.78CI + 1.09FTC + 2.40PERCIP + \frac{5.39\log(ESAL)}{SN}\right)$$

Equation 2.7

Where,

Age is pavement age.

FI is the Freezing Index (℃.days).

CI is Cooling Index (℃).

FTC is Freeze-thaw cycles.

PERCIP is the average annual perception.

ESAL is the Equivalent Single Axle Load.

SN is the Structural Number.

2.9. Application of Optimization on Pavement Networks

The optimization application in PMS will be discussed in this section. Due to its complexity, infrastructure asset management comprises a vast array of interconnected factors. With these multifaceted elements of infrastructure asset management, it made sense to have more advanced engineering modeling and decision-making support tools and techniques to be on top of the required developments.

2.9.1. Background

The asset management concept strives to achieve a minimum LCC and a maximum LOS for any asset. To reach this valid objective, it is imperative to develop a tool that automatically evaluates the different valid and invalid solutions and examines their impact on LCC and LOS. Unfortunately, a simple tool cannot sort through the millions of valid and invalid solutions to find the near-optimal one because there are millions of both. Thus, optimization is a crucial asset management component for infrastructure as a decision-making support tool. It is defined as "*a branch of mathematics concerned with finding the optimum alternative to complex problems following the established objectives and constraints*" (Alyami 2012). Therefore, this research established optimization as a decision-making support tool for decision-makers to reach their goals (objectives) as described in the numerically developed model. In addition to linear programming, non-linear programming, integer programming, etc., there are many other optimization techniques such as particle swarm and genetic algorithms (Abu-Samra 2014). The two most commonly used optimization techniques for PMS at the project and network levels are linear and integer programming (Abu-Samra 2014).

2.9.2. Applications of Optimization on PMS

Gao (2004) defines integer programming as an optimization model where all decision variables have only integer values. For example, project-level maintenance strategies have unique integers ranging from 0 (Do Nothing) to 9 (Replacement) with increments of one. Decision variables are defined through x_{it} where; i refers to maintenance activities, and t refers to the year when maintenance action is applied.

An integer programming-based project-level PMS seeks to determine the x_{it} value for each year in a given project to achieve a near-optimal result. The integer programming is also known as combinatorial optimization since it can provide answers to questions such as "*Is there a particular arrangement*?"and " and "*How many arrangements of some set of discrete objects are possible*?". Asset managers involved in the decision-making process understand the integer-programming concept easily. For example, most highway agencies have two key decision variables: the M&R action application time and the strategy type applied. Despite this fact, there is a large number of combinations that fall in the feasible range (Gao, 2004).

Integer-programming models are typically challenging to solve due to two significant difficulties that are presented. First, the decision variables are integers, limiting the methods (algorithms) for dealing with them. "Combinatorial Explosion" is the second challenge (Fwa et al. 1996). For example, a network-level PMS with 500 projects would have ten different M&R strategies; for an analysis period of five years, $(5{,}000)^{\wedge 5} = 3.125 * 10^{\wedge 18}$ possible solutions. In order to find a solution that works, decades will be required.

As a result of these complexities, most of these models are solved using heuristic methods. They are approximate implementations of true optimization methods. Heuristic solutions are feasible solutions derived from a specific search method but are not guaranteed to yield an optimum. "Improving-search Heuristics Method" is a simple and effective method. This method starts with an initial feasible solution and iterates. The current solution is evaluated against its neighbors during each iteration, and a feasible solution is selected, resulting in a better objective value. A local optimum and heuristic solution can be developed by following this process. The solution obtained by this method will likely be a local optimum as opposed to a true optimum despite its effective improving-search algorithm. Many other methods have been explored to produce more robust algorithms for obtaining local optima, which is closer to the true optimal solution, so as to reduce the likelihood of obtaining a locally optimal solution that deviates significantly from the true optimal solution (Gao, 2004).

Genetic Algorithm (GA) is a widely applied method in PMS to solve an integer-programming model to solve a project-level or a network-level PMS (Fwa et al. 1996). Holland introduced GA in 1975 (Abu-Samra, 2014). This method involves identifying two feasible solutions. Every iteration involves combining previous solutions to create a new solution. The objective of this method is to parallel the process of natural selection in search of better solutions. This method can be applied in several ways. Most of the differences arise from selecting the current solution pairs or combining them to create new ones. A key idea of the concept relates to deciding which new and old solutions will survive in the next population as well as how to maintain diversity as the search progresses from one generation to the next. Despite the method's high potential, it is nonetheless a meta-heuristic solution, and it gives rise to the disadvantage of not finding a truly optimal solution with increasing complexity (Gao, 2004).

Linear programs are optimization models with linear objective functions and constraint functions in decision variables. Markov Chains in network-level PMS are mainly used for deterioration modeling to predict future performance measures (Gao, 2004). The pavement KPIs' and expenditures are examined after project-level PMS selects the M&R strategy annually based on the predetermined analysis period. This optimization approach aims to find the optimal solution for different combinations of M&R strategies, where the one with the lowest LCC and meeting the contractually agreed upon KPIs is chosen as the optimum solution.

Despite the benefit of reaching an optimal solution, some disadvantages were discovered besides the optimization problem's difficulties. The decision-makers of some highway agencies reported difficulties comprehending the optimization methods, so they questioned the results of the rehabilitation plans generated by those methods. As a result, the support for both financial and technical outcomes of such M&R action plans becomes increasingly complex (Zimmerman et al., 2000). Furthermore, some highway agencies were hesitant to use this method because the optimized results were so complex that they feared losing control of their programming and scheduling processes. As a result, many approaches have been proposed for PMS optimization of M&R strategy programming in recent years. A few of their components are described below (Akyildiz, 2004, cited in Abu-Samra, 2014):

1. Identification of the available network data
2. Evaluation of the existing objectives
3. Distinguishing the anticipated M&R actions
4. Forecasting of the possible pavement condition
5. M&R actions selection and allocation

The two critical elements in the different optimization approaches are optimization algorithms and deterioration forecasting models. Those elements differ depending on the method of analyzing the problem used by the researchers. For example, Mbwana and Turnquist (1996), cited in Abu-Samra (2014), proposed a network-based PMS based on a giant linear programming technique, converted from a dynamic programming formulation to minimize the overall network

LCC. An alternative approach is to model the network-level PMS by using goal programming. It is emphasized that the power of goal programming is its capability to accommodate conflicting objectives with different importance weights (Raviarala et al. 1997, cited in Abu-Samra (2014)).

Despite that, goal programming faces some disadvantages when incorporating the Markov Transition Probabilities as part of the optimization process. Due to the high computational demands needed, integer programming in this approach was proven to be incompatible with mega-scale networks. As a result, Raviarala et al. (1997) proposed a linear approach to attain the optimal multi-year maintenance network program. Nevertheless, the network condition assessment involved several tasks, including defining the pavement condition and creating a maintenance asset inventory, which controls the specifications of three key processes:

1. Identification of the required M&R action
2. Condition-treatment matching
3. Predicting the transition time for the treatment

As much importance is placed on selecting the optimization algorithm as the performance prediction model (Li, N. 1997). Consequently, the researchers concluded it is necessary to develop a deterioration model that considers M&R's impact on deterioration after it is applied. In addition, the Markov decision process ignores any direct impact of the application of M&R on the pavement's deterioration rate, assuming that the applied M&R has no effect on the pavement's deterioration rate. Yet, that is not the case in practice. To address this, researchers implemented a nonhomogeneous (Time-related) Markov decision process assuming a new deterioration rate based on Ontario Asphalt Deterioration Equation for the segment where the M&R strategy was applied (Li, N. 1997). In addition, a standard unit cost was defined for each M&R strategy and quantified, in terms of KPIs, the effects of each M&R intervention plan on pavement conditions. Finally, the developed model utilizes an integer programming method to select the most cost-effective M&R strategies each year in order to maximize the Benefits-Costs Ratio (BCR). The selected M&R strategies were required to meet specific predefined budget and performance constraints. Different M&R strategies were compared based on their unit costs and their effects on the pavement LOS in the future.

Linear programming was used to develop a network-level optimization model to maximize the network performance over the planning horizon within the available budget (Liu and Wang (1996), cited in Abu-Samra (2014)). Among the key outcomes are the following:

1. Future pavement condition forecasting
2. Budget allocation with respect to attained M&R plan.
3. Pavement sections' initial conditions vary according to the available data.

Furthermore, a comparison of three artificial intelligence approaches has been established by Rababaah (2005). The studied AI approaches are Multilayer Perceptron (MLP), Genetic Algorithms (GA), and Self-Organizing Maps (SOM). Computer vision was used in this comparison to improve the automatic crack detection on asphalt pavements. According to the study, MLP accuracy was 98.6%, GA accuracy was 98.2%, and SOM accuracy was 98.4%. Additionally, a multi-layer pavement maintenance program was developed that takes into account the uncertainties inherent in the deterioration model (Chootinan et al. 2006). The model was developed through simulation-based GAs to develop a pavement M&R plan based on a multi-year time frame. The deterioration model was calibrated first, and then a stochastic simulation was run to determine the uncertainty of the future pavement condition. As a result of considering uncertainty in future pavement conditions, the M&R budget and network performance were underestimated.

Finally, Tack and J. Chou 2002 investigated the efficiency of utilizing GAs while establishing pavement M&R plans. GAs demonstrated high viability in improving pavements' condition by determining which M&R strategies were most effective throughout the LCC analysis period. Therefore, the subsequent investigation was conducted to develop near-optimal solutions using two different GAs' techniques, Simple GAs' (SGA) and pre-constrained GAs' (PCGA). It was concluded that GAs' superior flexibility and scalability could handle different pavement deterioration models and M&R strategies better than dynamic programming. On the other hand, dynamic programming proved inadequate to adjust for new decision variables introduced in the model. As a result, it was concluded that SGA and PCGA are more practical and advantageous to employ rather than dynamic programming algorithms. Furthermore, other researchers concluded that GA is more suitable for optimization problems with many decision variables and constraints due to the advantages mentioned before (Cheu et al., 2004, cited in Abu-Samra, 2014).

2.10. Principal Components Analysis

PCA technique portrayal is attributed to two prominent persons, Pearson (1901) and Hotelling (1933) though it is frequently credited to the latter. PCA is mainly used to reduce a large number of variables into fewer uncorrelated factors called the principal components. These components present the variation in the original variables. The first component accounts for the most significant probable variation, and the second component accounts for the second-largest variation, which wasn't accounted for in the first one. This is why they are considered uncorrelated to the rest of the variables. It is also noted that the number of principal components equals the number of initial variables. The principal components are derived from the original variable set through a linear weighted equation (Krishnan 2010). These components can be interpreted in mathematical terms as per the following equation, where each component is substituted as a linear weighted combination of the original variables.

$$PC_m = a_{m1}X_1 + a_{m2}X_2 + \cdots + a_{mn}X_n \qquad \text{Equation 2.8}$$

Where;

PC_m represents the m principal component,

a_{mn} represents the weight for *m*th principal component and the *n*th variable,

X_n represents the n variable.

The principal components, when presented, are orthogonal to each other. This means that each component measures a different dimension in that data (Vyas and Kumaranayake 2006). One method to determine which number of components help represent the sample is Kaiser's criterion, where components with variances/eigenvalue equal to or greater than one are taken into consideration (Ding and He 2004). The original variables could be quantitative or ordinal, but using the ordinal scale is not practical. Also, extra caution should be worked out in case the sampling weights for the sample data sets is unequal (Abeyasekera 2005).

PCA can be envisaged in four parts: the data, the scores, the loadings, and the residuals. The data consists of the data set variables that need to be investigated. The scores describe the variation percentage in each principal component. The loadings designate the trend in the components, and each variable is part of the trend of any of the components. At the same time, the residuals explain the variation, which isn't part of the trend of the components (Bro and Smilde 2014). While PCA is considered among the commonly used statistical techniques for unsupervised dimension reduction analysis, K-means clustering is considered one of the widely used techniques for unsupervised learning data clustering. According to Ding and He (2004), both are closely related, and data clustering is considered a form of data reduction (Ding and He 2004).

2.11. Findings and Limitations

In summary, resilience has been recognized as a significant aspect of infrastructure management. Moreover, there have been widely different definitions of infrastructure system resilience available in the literature. Nevertheless, most of those definitions were associated with the disaster management concept, and resilience was assessed as an extreme hazard-based network feature. There has been very limited research on resilience considering asset management, which is essential for optimized M&R plans that account for both concepts. Moreover, indicators that reflect infrastructure resilience were not thoroughly investigated in the previously examined literature and needed further consideration. Resilience assessment models, such as the IIM model, need an intensive database availability for usage, which is not the case for most countries. Accordingly, other models should be used to mitigate the absence of such a database and reliable historical data. Also, the effect of previous non-extreme disruption events on resilience was not considered, though different scholars mentioned it. Hence, developing an index that reflects pavement resilience based on the predefined resilience indicators is essential while considering aging effects, deterioration, and extreme and non-extreme disruption events. Even though multiple optimization models exist for selecting near-optimal M&R plans for pavement networks, resilience-based decision-making has not been adequately explored in the literature. Limited research has been undertaken to develop optimization models that aim to maximize pavement resiliency within the existing budgetary constraints.

Accordingly, this research is directed to study resilience from the perspective of asset management, examining the cost tradeoff between preparedness measures, the effect of failures, and the resilience indicators. Scholars drew attention to the growing need for direct investments to enhance a system's resilience in the face of the anticipated disruption. Such investment should involve a prioritization approach to satisfy limited budget and time constraints and enhance the overall resilience of a road network. Hence, investigating the connection between resilience and other asset management concepts (e.g., condition, reliability, and vulnerability) is paramount.

CHAPTER 3 – RESEARCH METHODOLOGY

3.1. Research Framework

The main objective of this study is to develop a methodology to reduce maintenance and rehabilitation work costs for pavement networks by integrating resilience into the asset management concept. Hence, this will combine and reduce the overall costs of M&R activities for pavement networks through maintaining an appropriate network resiliency, based on the proposed definition for resilience in asset management while keeping pavement networks well maintained through their lifecycle.

Three sequential models are proposed to achieve research objectives, starting from models contributing to building the main resilience-based asset management framework. Then going through the post-disruption model, which optimizes M&R actions that can be translated to the asset recovery plan, and then finish with the pre-disruption model targeting enhancing the overall pavement network resilience while optimizing the resulting overall cost after a disruption. The main research framework is summarized and presented in Figure 3.1, and details of each model will be presented and discussed in the following sections.

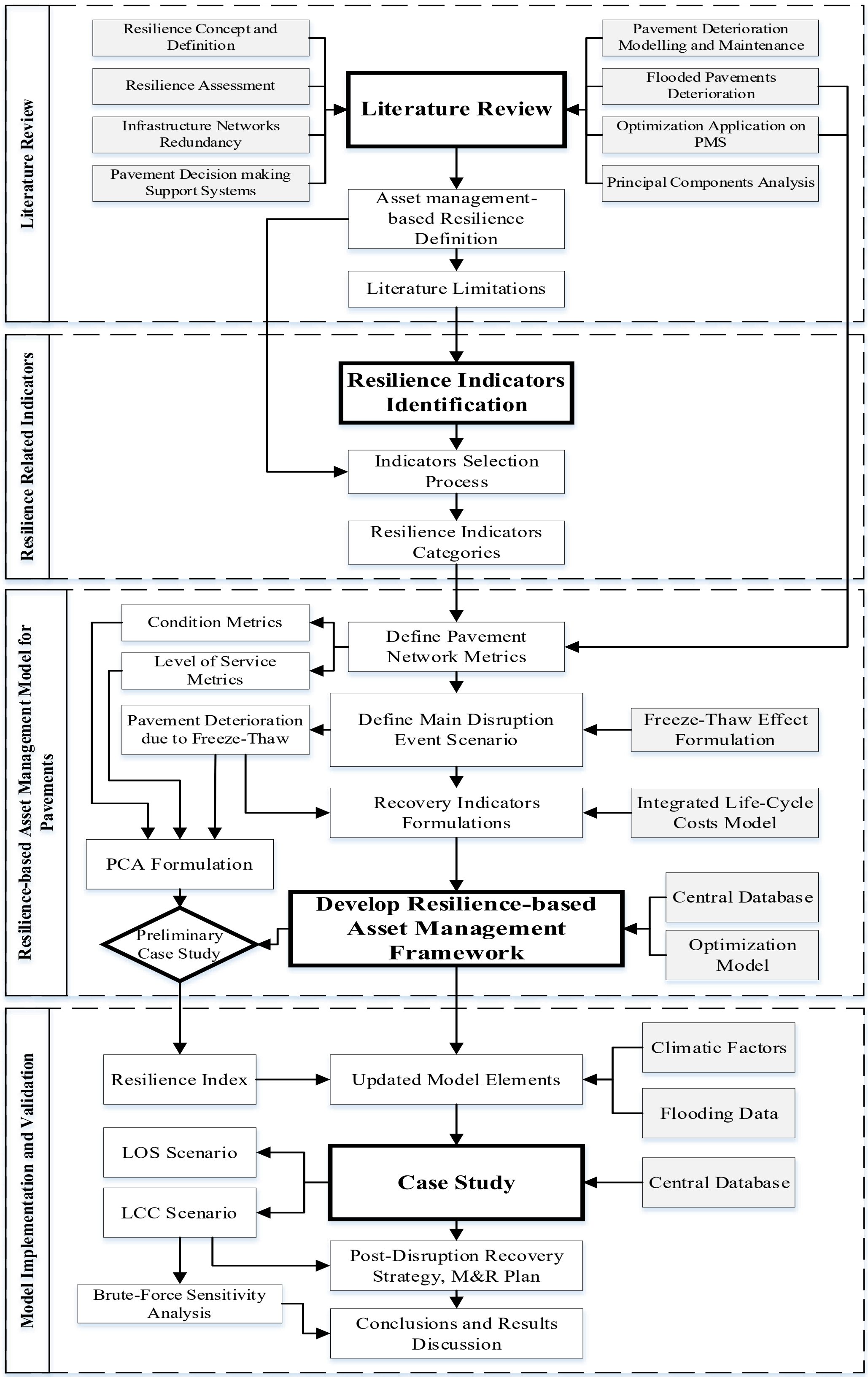


Figure 3.1: Proposed Research Methodology

3.2. Identification of Resilience Related Indicators

Resilience-related parameters that were used to predict resilience for infrastructure systems from previous research are used as the base to formulate resilience-related indicators. MacKenzie and Barker used infrastructure performance measures and interdependencies between different assets to predict infrastructure resilience (MacKenzie and Barker 2012). The MCEER framework interoperates technical, organizational, social, and economic aspects based on asset's Robustness, Redundancy, Resourcefulness, and Rapidity (Cimellaro et al. 2010). Network condition was also used to predict an infrastructure's resilience taking into consideration many aspects such as interdependency, the time factor, network type, asset criticality, and the disruption related criteria like its type, probability of failure due to each type (Gay and Sinha 2012; Ouyang and Dueñas-Osorio 2012; Bocchini et al. 2013). System recovery criteria such as resource availability, recovery time, and cost constraints are significant indicators of an asset's resiliency. Integrating original system performance with the pre-active rehabilitation measures was utilized to predict system resilience while considering system interdependency and the recovery process required to maintain the system's desired performance after a disruption (Gay and Sinha 2012).

Indicators identification was carried out through three steps shown in Figure 3.2. First, an intensive review of the previous literature related to research objectives was undertaken as a first step for collecting the indicators that affect resilience. Then, the second step aimed at filtering the collected indicators. Filtration was carried out based on the author's resilience perception and the proposed definition while conducting an extensive review of the available literature. Those indicators were collected from literature then several brainstorming stages were conducted to reduce those indicators to match the objective of this research and contest the author's definition. "Interdependency" was excluded and could be considered as an asset feature. "Asset criticality" was also excluded and assumed as an asset feature that could be included in the post-disruption recovery model. It is expected to assign an additional budget with a criticality increase. The same conclusion was reached for "region", which would be introduced as an asset feature in pre-disruption optimization models. It is also important to point out that LOS and asset condition should be defined independently when possible and as long LOS can be well-defined separately. Other authors used this observation in their first stages of resilience assessment to better understand the unique behavior of each indicator (Gay and Sinha 2012). The last step was selecting and categorizing the indicators, as shown in Table 3.1. The indicators were split into three categories as follows: (1) asset-based, (2) disruption-based, and (3) recovery. Within each category, the relevant indicators were placed. For instance, asset condition, LOS, and redundancy fell under the asset-based indicators. Still, the type of disruption, probability, and consequences of failure fell under the disruption-based indicators. Finally, recovery cost and time fell under the recovery indicators.

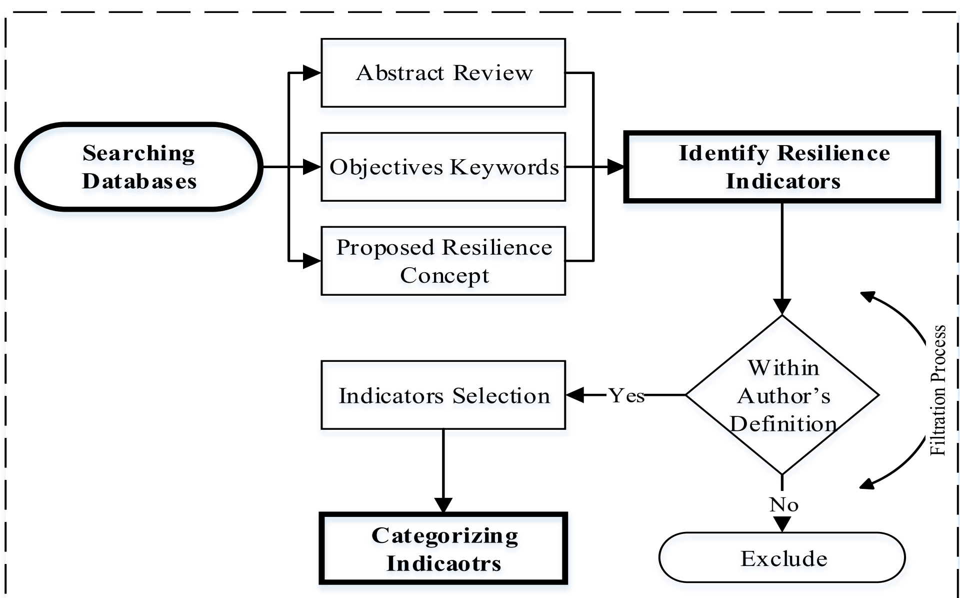


Figure 3.2: Resilience indicators identification process

Table 3.1: Asset Management-based resilience indicators

Category	*Indicator*	*Description*
Asset-Based Indicators	Asset Condition	The current asset condition with respect to its original one.
	Level of Service	"The defined service quality for an activity or service area against which service performance may be measured" (InfraGuide 2003).
	Redundancy existence	The system's capability to substitute degraded system elements and maintain system functionality after disruption or loss of function (Gay and Sinha 2012).
Disruption Based Indicators	Type of Disruption	The nature and cause of the disruption.
	Probability of failure	The chances that a specific asset will fail under a risk event.
	Consequences of failure	The negative impacts of a risk event.
Recovery Indicators	Recovery time constraints	The defined acceptable time for an infrastructure to recover to its original state after a disruption.
	Recovery costs constraints (Resourcefulness)	The defined budget, including resources available, to achieve the recovery work after a disruption.

3.3. Development of Resilience-based Asset Management Model for Pavement Networks

Based on the identified resilience indicators in section 3.2, each indicator should be interpreted in the form of a model that formulates it relative to pavement networks. Therefore, each resilience indicator will be formulated in the following sub-sections and based on previous research work, and the aptest model for this research will be determined.

3.3.1. Asset-based indicators

Three asset-based indicators were identified based on the identified resilience indicators: condition, LOS, and redundancy. For pavement, several measures were used to represent pavement condition and LOS. Several studies incorporated the International Roughness Index (IRI) to measure pavement LOS. IRI involves using numerous instruments (e.g., Laser mobile mounted devices), where their primary usage is quantifying the pavement roughness. According to Federal Highway Administration, the minimum acceptable IRI is < 1.50 m/km and < 2.70 m/km for good and acceptable road riding quality, respectively. Measurable performance indicators were investigated extensively in previous studies. Accordingly, the Level of Service was defined by several sub-indicators that summarize the quality of service to road users and can be summarized as per Figure 3.3 (Hass, R. et al. 2008; Haas. R. et al. 2009). IRI mainly reflects pavement functionality where it defines ride quality based on providing means of measurement of pavement surface roughness.

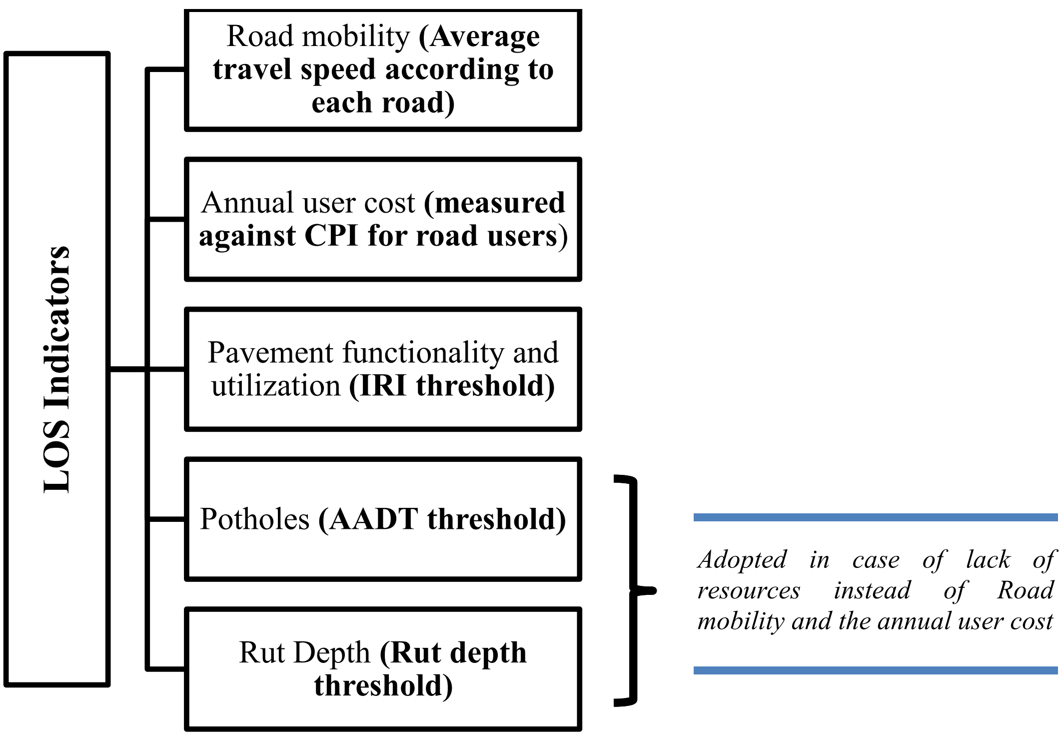


Figure 3.3: Pavement LOS sub-indicators

The average travel speed measures road mobility for the network based on corridors components class (e.g., Maintaining a minimum average speed of 50% of the required road speed limit as a threshold). The increase in the average road user costs per total network length should be less than the Consumer Price Index (CPI). Potholes and rut depth sun-indicators are usually implemented instead of road mobility and the annual user costs when dealing with small to intermediate pavement network service contractors. No potholes must be maintained as a threshold for roads with 1000 AADT or higher. This could be considered as a constraint for pavement network LOS maintenance and rehabilitation plan.

MEPDG method introduced an equation that combines the different sub-indicators to predict IRI over the design period or pavement lifecycle. This model includes potholes, rut depth, and a combination of transverse and longitudinal cracking resulting from road usage mobility and loads to predict IRI as per Equation 3.1. In addition, climatic impacts are also incorporated in the model, reflecting soil shrinking and swelling from frost-heave (Saha, 2011).

$$IRI = IRI_o + \frac{15}{1000}(SF) + \frac{4}{10}(FC_{Tot}) + \frac{8}{1000}(TC) + 40(RD) \qquad \text{Equation 3.1}$$

Where,

IRI_o is the initial IRI value (in/mi)

SF is Site Factor and can be calculated as per Equation 3.2

FC_{Tot} is a factor combining area of fatigue cracking resulting from alligator, longitudinal, and reflection cracking in the wheel path.

TC is the length of transverse cracking (ft/mi)

RD = Average rut depth (in)

$$SF = \ln((PERC + 1)\,(Fines\%)(FI + 1)) + (\ln((PERC + 1)\ \ (Clay\%)(PI + 1)))XAge^{1.5}$$

Equation 3.2

Where,

PERC is the average annual precipitation (in)

Fines % includes sand and silt (%)

FI is the average freezing index (Feh.days) (More information in section 3.3.3)

PI is the subgrade soil plasticity index.

Age is pavement age in years.

Pavement Condition Index (PCI) was introduced in several studies to measure pavement condition representing pavement distresses. Yet, many scholars correlated PCI to the IRI value obtained from pavement roughness, where quite a few mathematical functions were derived between indicators. Equation 3.3 presents a formula that predicts PCI based on the measured IRI value (Arhin et al., 2015). On a side note, the author believes that this Equation needs to be further developed to account for other factors that impact PCI prediction accuracy by affecting IRI (e.g., snow removal contributes to LOS condition in heavy snow areas) (Arhin et al. 2015). Finally, it is essential to point out that the case study data in Chapter 4 was used to verify the usage suitability of this formula in this study.

$$\log(PCI) = 2 - 0.436\log(IRI) \qquad \text{Equation 3.3}$$

One crucial consideration is predicting pavement condition through PCI during its life cycle. Several deterioration models for PCI were introduced using regression models based on historical data analysis (Hamdi et al., 2012). Another method used to estimate the PCI is using ANN based on the visual inspection results of the different distresses existing on the pavement (Shahnazari et al., 2012). Both models need significant data, yet the second model needs extensive visual inspection reports to estimate PCI. After reviewing different models and based on the data available from the pavement network case study, Equation 3.4 was considered the best fit for this study to model PCI deterioration, which was applied earlier in similar cases in Quebec (Hamdi et al. 2012).

$$PCI_i = 0.033i^2 - 2.688i + PCI_{in} \qquad \text{Equation 3.4}$$

where;

$\boldsymbol{PCI_i}$ is the anticipated PCI at year i; **i** is the year counter (%);

$\boldsymbol{PCI_{in}}$ is the initial PCI (%).

On the other hand, pavement structural condition is considered one of the most important indicators reflecting pavement condition. Therefore, pavement deflection measurements are vital to support the decision-making process when selecting the necessary pavement M&R actions and to provide the thresholds between those actions (Wang et al., 2003). SCI reflects the ratio between the effective Structural Number (SN_{eff}) and the required Structural Number (SN_{req}) (El-Badawy et al., 2011). The SN_{req} reflects the desired bearing capacity of pavement layers for the next 20 years based on pavement material and condition. While SN_{eff} reflects the current bearing capacity of pavement layers. Pavement thickness is needed to obtain SN_{eff} value, where many destructive and non-destructive testing methods can be utilized to calculate pavement layers thickness. Several studies utilized deflection Basin Parameters (DBPs) to estimate SN_{eff}. The most used parameter is the central deflection (D_0). Other parameters like Base Layer Index (BLI) are also utilized to evaluate the structural condition of a pavement, yet central deflection is considered the most important parameter. Area Under Pavement Parameters (AUPP) also showed great potential and accuracy in predicting SN_{eff} (Schnoor and Horak 2012).

There exist many measurement techniques for pavement deflection. Falling Weight Deflectometer (FWD) is one of the widely used methods. FWD is a non-destructive measurement technique that can effectively simulate the anticipated traffic loads on pavement surface and generate a data output for pavement deflection response. FWD is considered the most used technique for pavement structural evaluation in most PMSs. Either network or project levels, SCI can be utilized to serve both by providing more details that identify pavement sections that need maintenance, rehabilitation, or retrofit by providing adequate information about the base and subgrade quality (Park et al. 2005; Horak et al. 2015; Leiva-Villacorta et al. 2017; Mohammadi et al. 2019). One of the current drawbacks of pavement structural condition assessment models is the need to predict many parameters to obtain pavement deformation. Leiva-Villacorta et al. 2017 proposed a model capable of calculating pavement deformation to evaluate pavement condition. Hypothetically, many variables impact the amount of deformation that would occur in pavement during its life-cycle. Still, most are design-related factors, e.g., material properties, load duration, travel speed, etc. A significant amount of time and effort is needed to collect such variables data for the condition assessment of existing pavement. Therefore, a relationship was formed between pavement deflection and the deformation in the existing pavement. Data were obtained from GPR and FWD tests results. It is concluded that pavement thickness and load cycles are significant factors affecting pavement deformation and that higher pavement deflection values reflect high pavement deformation. This study indirectly considered the effect of the environmental conditions by calculating surface deflection, which reflects those effects. Horak et al. 2015 utilized the RAG pavement condition system to serve as a deflection bowl-based parameter scale. RAG ranges vary and must be modified according to pavement type: elastic, stiff or rigid, pavement base type, and traffic ranges. In addition, other parameters were included, such as SN_{eff}, to enhance the benchmarking process where such parameters serve as a preliminary evaluation method for a pavement structural condition.

As mentioned earlier, researchers have developed numerous parameters to evaluate a pavement structural condition with respect to FWD test results. Many transportation agencies utilize the deflection ratio and the normalized deflection ratio to evaluate a pavement network's structural condition and integrity. One parameter derived from deflection ratios and FWD test results is the normalized area parameter. Rigid pavements will demonstrate a great area parameter, while weak pavements will demonstrate a small area parameter. The normalized area ratio parameter delivers an excellent pavement structural condition assessment where the normalized area parameter was found to be strongly correlated to the deflection ratios (Saleh, 2016). Using the normalized area ratio parameter provides several advantages while assessing pavement structural condition. It reflects both subgrade and layers above's condition and their structural capacity. As mentioned earlier, the strong correlation between the area ratio and the deflection ratio is an added value and verification that supports the use of the normalized area ratio parameter. The normalized area ratio parameter also combines the maximum deflection value D_0, which reflects subgrade structural condition, and the area ratio, which reflects layers above subgrade structural condition. Accordingly, the normalized area ratio parameter delivers an all-inclusive pavement structural condition assessment. Equation 3.5 provides the formulation of the normalized area ratio parameter.

$$A'_r = \frac{50}{900\ X\ D_0^2}\left\{\left(\frac{D_0+D_{900}}{2}\right) + \sum_{i=50}^{850} D_i\right\} \qquad \text{Equation 3.5}$$

where;

$\boldsymbol{A'_r}$ is the normalized area ratio parameter

$\boldsymbol{D_0}$ is the deflection under the center of the load (mm)

$\boldsymbol{D_{900}}$ is the deflection at 900mm from the center of the load (mm)

$\boldsymbol{D_i}$ is the deflection at distance *i* from the center of the load (mm)

The higher the normalized area ratio parameter, the stronger the pavement structural capacity is. Table 3.2 demonstrates pavement structural capacity classification according to pavement type and the normalized area ratio parameter value.

Table 3.2: Pavement structural capacity classification (Saleh, 2016)

Pavement Type	**Pavement structural capacity classification** (Normalized area ratio value)			
	Weak	Fair	Good	Strong
Pavements with cement-stabilised base	< 1.00	1.0–2.0	2.0–3.0	> 3.00
Structural asphalts	< 0.60	0.6–1.0	1.0–1.5	> 1.50
Unbound granular with thin asphalts	< 0.25	0.25–0.4	0.4–0.7	> 0.70
Unbound granular with surface treatment	< 0.10	0.1–0.25	0.25–0.45	> 0.45

3.3.2. Redundancy Model

This study aims to deliver a maintenance and rehabilitation plan, mainly for road network segments. Accordingly, redundancy was suggested to be denoted as a factor representing the degree of flexibility in each pavement segment/link or network element. Redundancy exists in road networks in the intersections between road segments. Each intersection defines a particular destination, referred to as a node. Accordingly, the existence of more than one link or a different route of links that would achieve the same original functionality as an existing link is important in case of disaster. Most studies related to road network redundancy focus on node redundancy. The existence of alternate routes mainly defines a link's redundancy. Two redundancy-related criteria are considered while studying link redundancy undergoing disruption events: traffic flow and disruptive event impact (Jenelius, 2010). For simplicity, network spare capacity criteria will only be used to estimate pavement corridor redundancy, which matches the author's scheme of processing the network as an isolated network.

Accordingly, the redundancy indicator (RI) for node O existing in a road network can be formulated based on the entropy theory as follow:

$$RI(O) = \sum_{i=1}^{k} p_i \ln \frac{1}{p_i} \quad \text{Equation 3.6}$$

Where for a road network $\boldsymbol{p_i}$ is defined as the relative flow of a specific link $\boldsymbol{i}$ as follow:

$$p_i = \frac{f_i}{\sum_{i=1}^{k} f_i} \quad \text{Equation 3.7}$$

$where;$

$\boldsymbol{f_i}$ is the link flow at a specific time using a specific travel mode,

$\boldsymbol{k}$ is the total number of links with the connected flow to node O,

Several assumptions are considered in this study. First, this study considers only private road users as a travel mode. Second, road links with a flow greater than zero will only be considered, while links with zero traffic flow are emitted. Third, RI is normalized by dividing Equation 3.6 by ln(k) to obtain RI values ranging from 0 to 1 (Corson, 2010; El Rashidy, 2014). Fourth, RI functions as a junction redundancy indicator, while this research focuses on road corridors/links. Accordingly, link redundancy is assumed to be the least of that link's start and finish node RI. Finally, each node maintains two redundancy indicators, one reflecting the inbound flow redundancy and the other demonstrating the outbound flow redundancy. If the inbound or outbound flow is uniformly distributed over the links connected to that node, a maximum value of RI will be achieved (RI(O) = 1). In contrast, RI will be zero (RI(O) = 0) if all links are not transferring any flow except one link.

3.3.3. Disruption based indicators

The main cause of road network deterioration in Canada is the climatic conditions associated with the severe weather conditions, especially through winter and spring, ranging from freeze-thaw cycles to the increased moisture in pavement layers (Dore et al. 2005). Freeze-thaw cycles drastically impact pavement deterioration in Canada, where an average of 55% of the annual damage occurs from those cycles, especially the thaw period after winter (Jacobi, 2012). As stated earlier in previous studies, resilience is considered disruption-event specific. Thus, the Freeze-Thaw event was introduced as the main non-extreme disruptive event in parallel with the deterioration resulting from aging.

Freeze-thaw cycles cause severe damage to pavement, leading to accelerated deterioration in its performance and an apparent reduction in its service life. Accordingly, maintenance and rehabilitation costs increase significantly to maintain the desired LOS. Equation 3.3 presents pavement reliability-based resilient deteriorating model under Freeze-Thaw cycles effect in cold regions. This formula delivers the deterioration in resilient modulus for pavement, which denotes the stiffness of the pavement layers to resist deformation from the applied stresses (Si et al. 2014). After a thorough literature investigation, it was found that any degradation in the mechanical properties of the pavement layers, resulting from the Freeze-Thaw effect, will directly cause additional distresses and accordingly drop the pavement condition (Doré et al. 2005; Ma et al. 2014; Si et al. 2014). Thus, it was assumed that the degradation in the resilience modulus due to the Freeze-Thaw displayed in Equation 3.8 shall similarly occur to the pavement surface and structural conditions.

$$RM_x = RM_o + 151.92\, e^{-0.21X} - 151.92 \qquad \text{Equation 3.8}$$

where;

$\boldsymbol{RM_X}$ is pavement resilience modulus after X Freeze-Thaw cycles

$\boldsymbol{RM_o}$ is the initial pavement resilience modulus

X is the annual number of Freeze-Thaw cycles

Equation 3.8 represents an exponential model for the effect of the freeze-thaw cycle on the R.M of asphalt pavement. This model was verified for flexible pavements and is believed to provide an excellent relationship between the Freeze-Thaw effect and R.M (Ma et al., 2014). Since most pavements in Canada are flexible pavements, this model would be applicable in this study (Saha, 2011). A similar approach was used to predict the change in pavement resilience modulus due to climatic changes using the MEPDG methodology. The AASHTO-1993 and MEPDG both provide means of pavement design. Yet MEPDG delivers effective results, especially cost-related, where it incorporates the existing climate conditions and their effect on pavement condition into pavement design procedures. As a result, this reduces the over and underestimation of pavement designs resulting from using AASHTO-1993. This limitation in the AASHTO-1993 is due to its empirical derivation from pavement tests conducted almost 50 years ago (Saha, 2011). MEPDG adopts a similar but more detailed approach by incorporating Enhanced Integrated Climatic Model (EICM). The EICM works as a simulation tool for the climatic conditions surrounding pavement during its life cycle. One of the outputs of EICM is an adjustment factor for resilient pavement modulus to use for pavement design in MEPDG. MEPDG utilizes different performance indicators that reflect pavement performance based on its condition. These performance indicators include IRI, rutting, fatigue, longitudinal and transverse cracking. To aid MEPDG methodology, Transportation Canada Association developed 232 weather stations around Canada to record the climate data, as shown in Table 3.3.

As mentioned before in section 3.3.1, it is important to predict and calculate the FI to consider its effect on pavement IRI. FI measures the below-freezing temperatures in terms of time intervals and temperature value during one freezing season. The thawing process of the generated ice inside pavement that occurs after the freezing season creates the most damage and loss of pavement strength. The average FI was reported to equal 1593 ºC-days in Quebec according to a report prepared by different Canadian governmental entities according to weather stations data.

On the other hand, flooding is considered the most common extreme disruptive event in different regions in Canada (Government of Canada, 2015). Furthermore, flooding and Freeze-thaw are correlated since flooding in Canada usually occurs after the thawing period in spring. Nevertheless, each has its effect on the pavement network. Accordingly, flooding and its effect are introduced as this research's main extreme disruptive event. As mentioned in section 2.7, Equation 2.7 did not consider the impact of extreme disruptive events. Accordingly, Equation 3.9 was developed to predict IRI change due to extreme flooding events. As a result, only four parameters had an effect related to the IRI value. In contrast, other parameters had an insignificant impact (Shamsabadi et al., 2014).

$$\%\Delta IRI = 10.70 - 1.66NIRI + 7.30NDepth - 2.10NDuration + 14.30Depth * IRI$$

Equation 3.9

Where,

$\%\Delta \boldsymbol{IRI}$ is the percentage change in IRI

$\boldsymbol{NIRI}$ is the normalized IRI value before flooding

$\boldsymbol{NDepth}$ is the normalized flooding depth

$\boldsymbol{NDuration}$ is the normalized duration of the flood

Table 3.3: Recorded climate data in Quebec (Saleh, 2016)

Provinces of Canada	*Weather Stations*	*Mean Annual Air Temp. (°C)*	*Mean Annual Precp. (cm)*	*Average annual freezing index (°C-days)*	*Start date of Data*	*End date of data*	*No of available months*	*Climt. Zones*
Quebec	Bagotville Airport	3	92.6	1513.7	7/1/1987	6/30/2007	240	4
	Baie-Comeau Airport	2	99.3	1350.5	2/1/1974	1/31/1994	240	4
	Gaspe Airport	3.6	109	1130.4	7/1/1987	6/30/2007	240	4
	Gatineau Airport	5.6	0	1096.9	10/1/1987	9/30/1991	48	2
	Grindstone Island	4.5	97.2	696.4	4/1/1968	1/31/1983	178	4
	Inukjuas Airport	-6.6	48.9	3305.2	9/1/1976	9/30/1992	193	2
	Kuujjuaq Airport	-4.9	51.1	3068.2	7/1/1987	6/30/2007	240	4
	La Grande Riviere Airport	-2.3	68	2608.2	7/1/1987	6/30/2007	240	4
	Maniwaki U Airport	3.3	97.7	1414.5	1/1/1990	9/30/1992	33	4
	Mont-Joli Airport	3.8	89.3	1116.4	7/1/1987	6/30/2007	240	4
	St-Hubert Airport	6.4	101.5	934.4	5/1/1974	4/30/1994	240	4
	Mirabel Int. Airport	5.7	106.4	1027.7	7/1/1987	6/30/2007	240	4
	Pierre Elliot Trudeau Int. Airport	7.1	99.2	840.7	7/1/1987	6/30/2007	240	4
	Nitchequon	-3.8	85.4	2855.2	12/1/1965	11/30/1985	240	4
	Jean Lesage Int. Airport	4.8	54.3	1111.5	7/1/1987	6/30/2007	240	4
	Roberval Airport	2.9	85.3	1564.2	7/1/1987	6/30/2007	240	4
	Rouyn Airport	2.4	0	1663.1	7/1/1987	6/30/2007	240	2
	Sept-Iles Airport	1.6	87.3	1460.5	7/1/1987	6/30/2007	240	4
	Ste Agathe DesS Monts		117.5	1303.7	6/1/1972	5/31/1992	240	4
	Val-D'or Airport		90.7	1775.3	12/1/1975	11/30/1995	240	4

3.3.4. Recovery indicators

Two important indicators play a great role in disruption and aftermath reduction. First, accurate deterioration and life-cycle prediction models are two great assets necessary to obtain a better maintenance and rehabilitation intervention/recovery plan while combining regular and extreme disruption events. Second, pavement network damage patterns due to certain types of events would also be of great use in developing the required intervention strategy (Lu et al., 2017). Accordingly, several questions arise; (1) what are the available intervention actions available for post-disruption recovery? (2) What is the effect of each action on pavement resilience, and what are the corresponding costs for that action? And (3) How long would it take to perform that action?

Based on the abovementioned questions, recovery indicators are used to represent the time and cost required for the recovery activities after undergoing a certain disruption. Based on the assumption of Freeze-Thaw cycles and flooding events, time and cost will be linked to the intervention actions. Thus, four M&R interventions were considered in this model as follows: (1) do nothing, (2) routine maintenance, (3) minor rehabilitation, and (4) major rehabilitation/reconstruction (Meneses and Ferreira 2015). Table 3.4 presents the unit cost and time for each intervention action, their application range, and their impacts on the PCI. Rehabilitation was divided into two categories to reflect the current practices in pavement rehabilitation. At the same time, routine maintenance was assumed to occur regularly to maintain the same decay affecting pavement during its life cycle based on the used regression deterioration model for pavement condition.

Table 3.4: M&R Intervention actions (Meneses and Ferreira 2015; Holt et al. 2011)

Maintenance action	**Notation in 2nd level decision variables**	**PCI application range**	**Impact on PCI (%)**	**Recovery Time (hr/unit)**	**Recovery Cost ($/unit)**
Routine Maintenance (e.g., Crack filling, sealing, etc.)	-	-	-	0.30	10
Minor Rehabilitation (Mill Overlay HMA)	1	65% - 100%	75%	0.45	15
Major Rehabilitation (Deep Patching)	2	40% - 65%	90%	0.60	20
Reconstruction	3	0% - 40%	100%	1	30

The mathematical formulation of the impact of the maintenance actions (decisions variables) is displayed through equations 3.10 to 3.12

$$PCI_{ik} = \begin{bmatrix} Do\ Nothing & 0.033i^2 - 2.688i + PCI_{in} \\ Overlay & (0.75)PCI_{in} \\ Deep\ Batching & (0.90)PCI_{in} \\ Reconstrcution & PCI_{in} \end{bmatrix}$$ Equation 3.10

$$NCI_i = \sum_{i=1}^{n} [W_k * PCI_{ik}]$$ Equation 3.11

$$NCI = \overline{NCI_i}$$ Equation 3.12

where;

$\boldsymbol{PCI_{ik}}$ **i**s the pavement condition index at year i for corridor k,

$\boldsymbol{PCI_{in}}$ is the initial pavement condition,

$\boldsymbol{NCI_i}$ is pavement network average condition at year i,

$\boldsymbol{NCI}$ is pavement network average condition.

For each intervention action scenario, costs and time are calculated based on Table 3.2 and the concept of the time value of money. Thus, a financial model is developed to account for those costs and later implemented and linked into the optimization model. The same goes for intervention time. The mathematical formulation for the model is presented through equations 3.13 to 3.15.

$$RC_{ik} = [X_{ik} * RUC_x * L_k]$$ Equation 3.13

$$NRC_i = \sum_{k=1}^{s} [RC_{ik}]$$ Equation 3.14

$$NRC = \sum_{i=0}^{T} [NRC \quad * (1 + in)^I]$$ Equation 3.15

where;

$\boldsymbol{RC_{ik}}$ is the rehabilitation/Recover cost of corridor k at year i,

$\boldsymbol{X_{ik}}$ is a binary decision variable with "0" representing the "Do nothing" option and "1" representing the "Rehabilitation/Recovery" action,

$\boldsymbol{RUC_x}$ is the recovery unit cost of decision variable X,

$\boldsymbol{L_k}$ is corridor length,

$\boldsymbol{NRC_i}$ is network recovery cost at year i,

$\boldsymbol{NRC}$ is the net present value of the cumulative network recovery costs over the study planning horizon $\boldsymbol{T}$ and $\boldsymbol{in}$ is the annual interest rate percentage.

$\boldsymbol{I}$ is the cash flow time

3.4. Preliminary Optimization Model

The key motivation behind this research is developing an index that signifies an asset's resilience according to the definition proposed by the author, which combines asset management approaches into resilience assessment. Accordingly, the Resilience index shall be computed through the weighted-sum mean method. In addition, each indicator will be assigned a calculated weight that reflects its impact and importance on the overall RS displayed in Equation 3.16. The proposed methodology to acquire and assign indicators weights is presented and discussed in Section 3.5. N_{ni} values range between [0-1].

$$RS_i = \sum_{n=1}^{q} W_n . N_{ni} \qquad \text{Equation 3.16}$$

$\boldsymbol{RS_i}$ is the Resilience Index for the corridor at year i (%);

n is the counter for the indicators;

$\boldsymbol{q}$ is the total number of indicators;

$\boldsymbol{W_n}$ is the importance weight for indicator n (%);

$\boldsymbol{N_{ni}}$ is the normalized value for the different indicators n at year i.

Reaching the balance between recovery cost and asset resilience is a key asset management decision. The existence of numerous valid M&R intervention scenarios increases the decision-making process complexity manifold. For instance, the number of solutions for ***s*** pavement sections, through ***T*** years planning horizon, considering the three intervention actions along with the "Do Nothing" option, would be 4^{s*s}. The wider the range of the decision variables, the more exponential and more computationally complex the optimization problem will become because of the greater spectrum of possible combinations. Furthermore, the need to place additional constraints (e.g., annual budget limitation, minimal LOS and condition, etc.) escalates the problem's difficulty in limiting the search space for valid solutions. Thus, there is a need for an optimization engine that undertakes trade-off analysis among various M&R intervention scenarios and supports the decision-makers in selecting a near-optimal M&R intervention plan throughout the planning horizon.

The optimization engine works through a Genetic Algorithm engine. GA is derived from biological systems, which simulate the natural survival of the fittest. Each string of chromosomes consists of genes, which represent a solution. Mutation and crossover operations are carried out by exchanging genes where new solutions are generated and evaluated to replace the weaker members of the population. The process continues until a satisfactory solution is met. Throughout this process, four key factors impact the performance of the output: (1) number of generations; (2) population size; (3) mutation rate; and (4) crossover rate (Elbeltagi and Tantawy 2005 cited in Abu-Samra 2014).

Advanced spreadsheet modeling and Evolver™ Version 7.0 are utilized to develop the optimization model. It functions through a powerful optimization engine that is designed to meet the performance thresholds and limited monetary and temporal constraints. As highlighted earlier, the key motivation behind this study was developing an overall resilience index that incorporates the recovery cost, recovery time, redundancy, LOS, and condition. Thus, the objective of the optimization engine is mathematically formulated to minimize the International Roughness Index, IRI, (Maximize LOS) at the end of the planning horizon, as shown in Equation 3.10. The decision variables are modeled in two levels to simplify the problem's complexity and minimize the search space. The first level was formulated using binary coding rules, where "0" represents the "Do Nothing" option and "1" represents the existence of an intervention/recovery action. Given the fact that three M&R actions were considered in this study, and to indicate the different maintenance actions that need to be undertaken in different condition states, a second level was formulated using a set of SMART rules that select the appropriate intervention action based on the condition, and LOS application ranges defined earlier in Table 3.2. Thus, a "1" in the first level of decision variables might represent either "1" or "2" or "3" in the second level, which reflects the most appropriate intervention action, depending on the PCI application ranges. Finally, five constraints are set to ensure that the chosen intervention scenarios are valid. Similar to the first level of decision variables, the constraints are modeled through binary coding rules, where "0" represents meeting the constraint and "1" represents failing to meet the constraint. The five constraints are as follows: (1) annual recovery cost should not exceed the available annual budget, (2) annual recovery time should not exceed the total number of available annual resources, represented by working hours, (3) PCI of any section at any point of time throughout the planning horizon should meet the minimal condition threshold, (4) IRI of any section at any point of time throughout the planning horizon should meet the LOS threshold, and (5) number of annual interventions should not exceed 20% of the total number of sections in the network to avoid extreme service disruption.

The mathematical formulations of the constraints are mathematically formulated, as shown in Equations 3.17 through 3.22.

Minimize overall weighted average network IRI;

$$\frac{1}{s}\ \sum_{k=1}^{s}\sum_{i=1}^{T} \mathrm{W_k} * IRI_{ik} \qquad \text{Equation 3.17}$$

Subject to the following constraints:

$$RC_i \leq \text{Annual budget} \qquad \text{Equation 3.18}$$

$$RT_i \leq \text{Annual working hours} \qquad \text{Equation 3.19}$$

$$PCI_i \geq PCI_{th} \qquad \text{Equation 3.20}$$

$$IRI_i \leq IRI_{th} \qquad \text{Equation 3.21}$$

$$\sum_{k=1}^{s} X_{i_k} \leq 20\% * \mathrm{s} \qquad \text{Equation 3.22}$$

$$\textbf{Decision variables} = \begin{bmatrix} X_{i_k} & \cdots & X_{T_k} \\ \vdots & \ddots & \vdots \\ X_{i_s} & \cdots & X_{T_s} \end{bmatrix}$$

For I_{t_o} = 0, 1, … 10
t = 1, 2, … T
o = 1, 2, … O

where;

$\boldsymbol{RC_i}$ is the recovery cost at year i ($);

$\boldsymbol{RT_i}$ is the recovery time at year i (hrs);

$\boldsymbol{PCI_i}$ is the pavement condition index at year i (5);

$\boldsymbol{PCI_{th}}$ is the minimal acceptable pavement condition index (%);

$\boldsymbol{IRI_i}$ is the international roughness index at year i;

$\boldsymbol{IRI_{th}}$ is the international roughness index predefined threshold;

X_{i_k} is the intervention action for corridor k (e.g. “0” for “Do Nothing and “1” for “Intervention action”).

k is the corridor counter

s is the total number of corridors

T is the planning horizon

3.5. Principal Components Analysis Framework

One significant usage of PCA is to use the first principal component as an index that summarizes the date set (Abeyasekera 2005). This could be implemented in this research by adjusting the weights of the resilience indicators to have a standard weight for the different used predefined indicators and thus obtain a reliable first component that could represent the required resilience index for each network sector and the whole network.

3.5.1. Data Standardization

Since each indicator's date range is different, all indicators' ranges should be standardized so that each indicator would contribute approximately consistently to the principal components. A common method of variables scaling is normalization, where the range of each indicator would be in the range of [0,1] as per the following equation 3.23 (Mohamad and Usman 2013);

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \qquad \text{Equation 3.23}$$

Where;

x' is the normalized value,

x is the original value,

$\max(x)$, $\min(x)$ are the maximum and minimum values in the dataset, respectively.

Another widely used method for variables scaling is standardization. It's commonly used in machine learning algorithms where data may include numerous dimensions. This is typically done through the following equation 3.24, which would be adopted in this research (Mohamad and Usman 2013);

$$x' = \frac{x - \bar{x}}{\sigma} \qquad \text{Equation 3.24}$$

Where;

x' is the normalized value,

x is the original value,

$\bar{x}$ is the mean of the indicator,

σ is the standard deviation of that indicator.

3.5.2. PCA-based Resilience Index

When performing PCA, the variables are formed in a linear combination, where each principal component output is a combination of the different input variables. At the same time, an index is considered an amalgamation of different variables. In another way, to describe resilience or assess it based on the author's definition at the end of section 2.2, it's needed to define and select the different resilience-related variables/indicators, study the selected variables and their relations then establish the method to create the index from these variables, and validate it as the last step. A similar approach was used to create an index to assess community development in Montreal (Amin and Tamima 2015). PCA was the preferred method over AHP/ANP techniques to assign resilience indicators weights, where PCA is more data-based oriented and eliminates the subjectivity of the abovementioned techniques.

Variables selection was carried out in Section 3.2. Several considerations were taken with the selected indicators. First, the variables reflect the proposed asset management-based resilience definition. The selected indicators show unidimensional criteria where each measures a specific resilience aspect. While collecting the predefined indicators, it was decided that this research opts to integrate resilience into the asset management concept and thus shows how specifically the indicators were selected. Each indicator should show the amount of variance in its data; theoretically, each pavement corridor would have a different dataset than other corridors. This summarizes the first step toward creating the desired resilience index. Finally, the selected indicators were investigated relative to the pavement. Correlation analysis was applied to determine the empirical relationship between them and whether they reflect the same resilience concept targeted in this research to obtain more insight into the relationship between the different indicators. Nevertheless, integrating the predefined indicators would sufficiently reflect the concept of resilience targeted in this research based on the author's definition.

The next step is index formulation. Figure 3.4 presents the framework used to apply the PCA on a data sample to assign importance weight to each predefined resilience indicator. Resilience-related indicators were defined and demonstrated based on previous work conducted by other researchers analyzing resilience from a different perspective than asset management. Since each indicator represents a certain dimension in resilience and is measured in different units, scaling shall be conducted, as mentioned earlier, using the standardization formula as in Equation 3.24. Before scaling the predefined indicators, an important step is to make all the indicators directly related to resilience. IBM SPSS® is used to conduct the PCA on the predefined indicators. PCA output mainly generates a number of components equal to the number of the predefined input variables representing indicators in this study. Components with eigenvalue less than one are neglected. Each component demonstrates the variation in the input data but in a new dimension. Principal components loadings are also part of the output designating the contribution of each input variable in each output principal component. Principal components loadings shall be extracted for each variable to determine the importance weight for each input variable using the following formula presented in Equation 3.25;

$$W_n = \frac{w_{1n}PC_1^{Var\%} + w_{2n}PC_2^{Var\%} + \cdots .... + w_{mn}PC_m^{Var\%}}{\sum_{m=1}^{m} PC^{Var\%}} \quad \text{Equation 3.25}$$

W_n represents the *n*th variable weight,
w_{mn} represents the weight for *n*th variable in the *m*th principal component,
$PC_m^{Var\%}$ represents the percentage of variability for *m*th principal component (Principal component score).

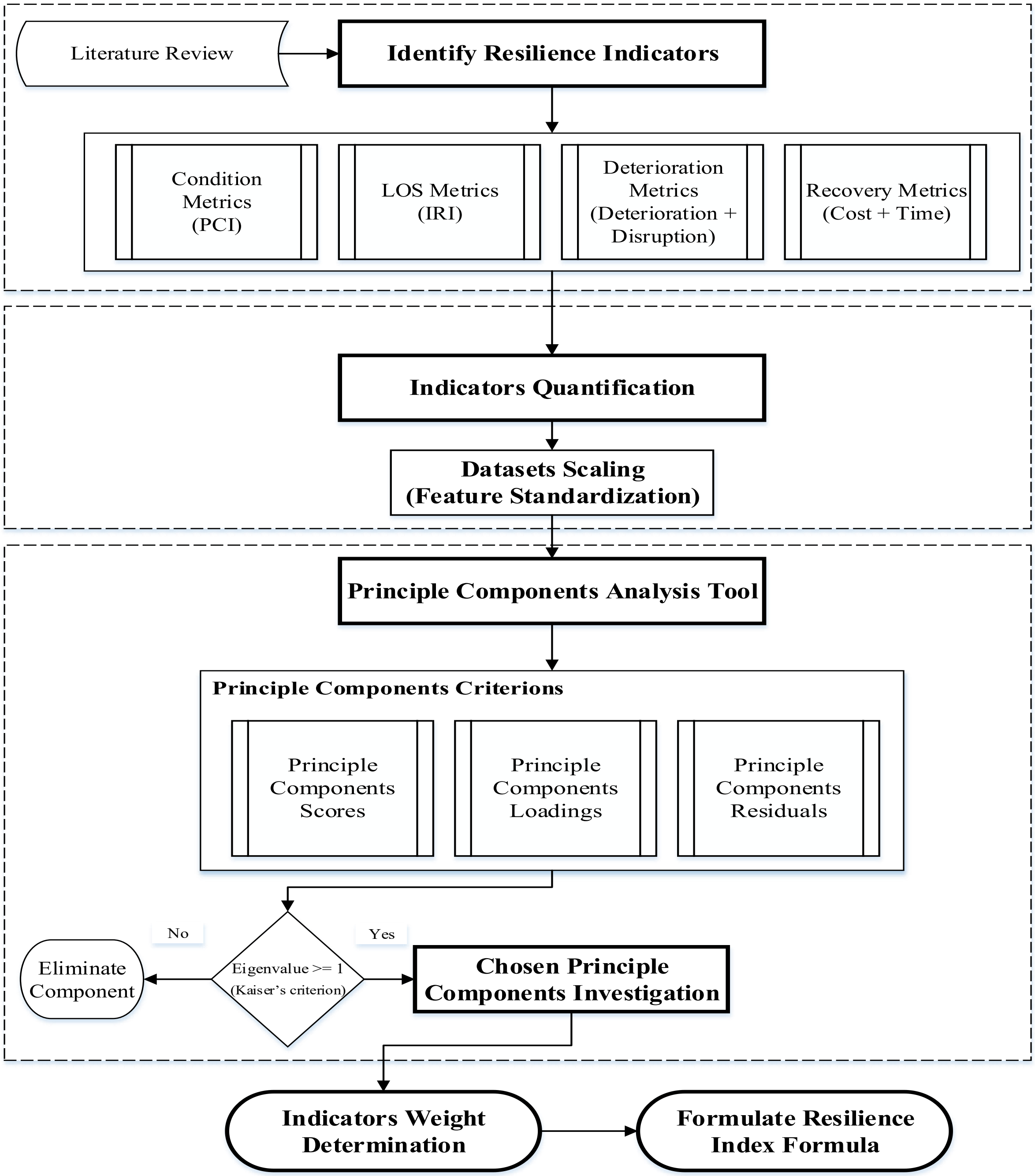


Figure 3.4: Principal Components Analysis proposed methodology

After building the resilience index, validation of the resilience index should take place to confirm that it measures what it is intended to measure and to examine the extent of its accuracy. According to Webb et al. (1966 cited in Bryman 2004), using more than one method of data analysis is called triangulation, resulting in greater confidence in the findings. Therefore, it could be considered a validation method.

Clustering is considered an unsupervised classification/algorithm that extracts clusters from the data itself. On the other side, classification depends on predefined clusters. Thus, the clustering technique opts for recognizing the different groups that could exist in a sample in general. So, units are categorized according to their similarity. The clustering technique would provide several groups representing a distinct set that could later be used as a second data analysis tool. It shall distinguish between different pavement network data based on the predefined indicators and examine the resulting clusters and their matching extent with the obtained RS for the same pavement sectors (Abeyasekera 2005). Later on, model validation is accomplished through the primary model implementation in the main case study.

This chapter includes in detail the research methodology used in this study. Then, the process of defining the different resilience indicators was illustrated in detail. In addition, these indicators were formulated with respect to the pavement network, reflecting how resilience indicators are formulated based on the field of study. Then, the proposed resilience definition was converted to an optimization problem, and the preliminary optimization model was illustrated. Finally, the formulation of the RS and the methodology involved were demonstrated.

CHAPTER 4 – PRELIMINARY IMPLEMENTATION OF METHODOLOGY

4.1. Introduction

The model was applied to a 3.75 KM residential road network in Kelowna city, British Columbia province, Canada. The network data was collected from the open-source City of Kelowna GIS maps (City of Kelowna 2016). The network was divided into 20 corridors for undertaking the study analysis. The condition rating and the IRI were estimated based on the Canada infrastructure report 2016 to mimic the same pavement conditions (FCM 2016). Table 4.1 displays the physical, spatial, and condition-related data of the 20 corridors under this study. As visualized in Table 4.1, the IRI fluctuated between good, acceptable, and not acceptable IRI values according to FHWA values for measuring road quality, as shown in Table 4.2 (Arhin et al. 2015). Due to data availability limitations, not all resilience indicators were used to demonstrate the proposed model in this study.

Table 4.1: Studied network criteria per corridor

Corridor ID#	PCI (%)	IRI (in/mile)	Length (m)	Number of lanes	Section Area (m²)	Average Annual Daily Traffic (AADT)	Number of surrounding roads
1	96%	97.47	143	3	1,287	12,000	2
2	73%	137.01	146	4	1,752	8,000	2
3	79%	127.13	151	4	1,812	10,000	1
4	79%	127.13	275	2	1,650	11,000	3
5	66%	148.1	184	3	1,656	7,000	2
6	66%	148.1	278	4	3,336	9,500	3
7	94%	100.99	294	4	3,528	10,500	3
8	88%	111.42	158	2	948	8,500	4
9	94%	100.99	168	4	2,016	6,800	1
10	84%	118.59	187	4	2,244	7,500	3
11	44%	185.9	228	3	2,052	9,000	4
12	52%	172.9	134	4	1,608	6,000	4
13	73%	137.01	113	4	1,356	5,000	3
14	88%	111.42	154	4	1,848	11,000	4
15	44%	185.9	258	2	1,548	10,000	2
16	73%	137.01	124	3	1,116	6,000	2
17	59%	160.17	293	2	1,758	9,000	2
18	44%	185.9	103	2	618	12,000	4
19	73%	137.01	119	2	714	9,000	1
20	52%	172.9	231	4	2,772	8,000	4

* Truck Percentage is 10% * Lane Width is 3.00 m * Pavement corridors are located in a residential area.
* Average speed is 25 km/hr. *Traffic Growth Rate is 5%

Table 4.2: IRI pavement thresholds according to FHWA (Arhin et al. 2015)

Road Quality	***IRI (in/mile)***
Good	< 95
Acceptable	< 171

4.2. Main Assumptions and Model Development

Optimization was used as indicated in Chapter 3 to establish the author's resilience definition. Where to satisfy the definition's objective and constraints, optimization would work as a practical tool to achieve that. For ease of calculations at this research stage, redundancy will be given different static values for each corridor. Nevertheless, the redundancy value for each corridor should be dynamic. It varies according to the type of maintenance performed, the existence of new pavement corridors construction plans, and the severity of the predicted disruption event on each corridor. The effect of the age and Freeze-Thaw on asset deterioration was forecasted using the model presented earlier to predict each corridor's anticipated PCI and IRI. The intervention actions were selected based on pre-defined meta-heuristic rules, where the intervention actions rely on the corridor corresponding PCI value as presented in Table 3.2. Based on the author's proposed resilience definition, LOS is the main threshold for undertaking an intervention. Accordingly, 50% and 171 in/mile values for PCI and IRI, respectively, were used as the unacceptable thresholds for each corridor. The initial RM value was assumed to be 625.33 KPa. The interest rate was assumed at 2%. The optimization attributes could be summarized as follows: (1) crossover rate: 80%, (2) mutation rate: 20%, (3) stoppage criteria: time-based.

To combine network results for the condition, LOS, and redundancy, corridor length was used to compute the weight of each segment from the total network length. The corridor weight was determined based on the percentage of the length of the sections over the total network length. For instance, the length of corridor one is 143 m, and the total network length is 3.75 KM. Thus, corridor one weight would be computed as the percentage of its length divided by the total network length, which results in a 3.82%, as illustrated in Equation 4.1. Accordingly, the network's annual condition, LOS, and redundancy state could be computed as shown in Equation 4.2. The condition, LOS, and redundancy of the network at the end of the planning horizon are equal to the last year's condition, LOS, and redundancy. Yet, the recovery indicators (e.g., recovery cost and time) were summed up, as shown in Equation 4.3, to compute the annual costs and time to undertake the recovery actions, as they are represented in monetary and temporal terms, respectively. The cumulative recovery cost and time is simply the summation of the recovery cost and time throughout the planning horizon.

$$W_k = \frac{L_k}{L_{net}} \quad \text{Equation 4.1}$$

$$\text{Cond}_{Net_i} \text{or LOS}_{Net_i} \text{ or Red.}_{Net_i} = \sum_{k=1}^{s} \frac{(L_k * Cond_{k_i} \; or \; LOS_{k_i} \; or \; Red._{k_i})}{L_{net}} \quad \text{Equation 4.2}$$

RC_{Net_i} or $RT_{Net_i} = \sum_{k=1}^{s} RC_{k_i}$ or RT_{k_i} Equation 4.3

where;

$\boldsymbol{W_k}$ is the weight of corridor k (%);

$\mathbf{L_k}$ represents the length of corridor k (m),

$\boldsymbol{L_{net}}$ is the total length of the sections within the network (m),

$\mathbf{Cond}_{\boldsymbol{Net_i}}$ is the condition of the network at year i (%);

$\mathbf{LOS}_{\boldsymbol{Net_i}}$ is the overall level of service of the network at year i;

$\mathbf{Red.}_{\boldsymbol{Net_i}}$ is the overall redundancy index of the network at year i (%);

k is the pavement sections counter;

s is the total number of sections;

$\mathbf{RC}_{\boldsymbol{Net_i}}$ is the recovery cost of the network at year i ($);

$\mathbf{RT}_{\boldsymbol{Net_i}}$ is the recovery time of the network at year i (hrs);

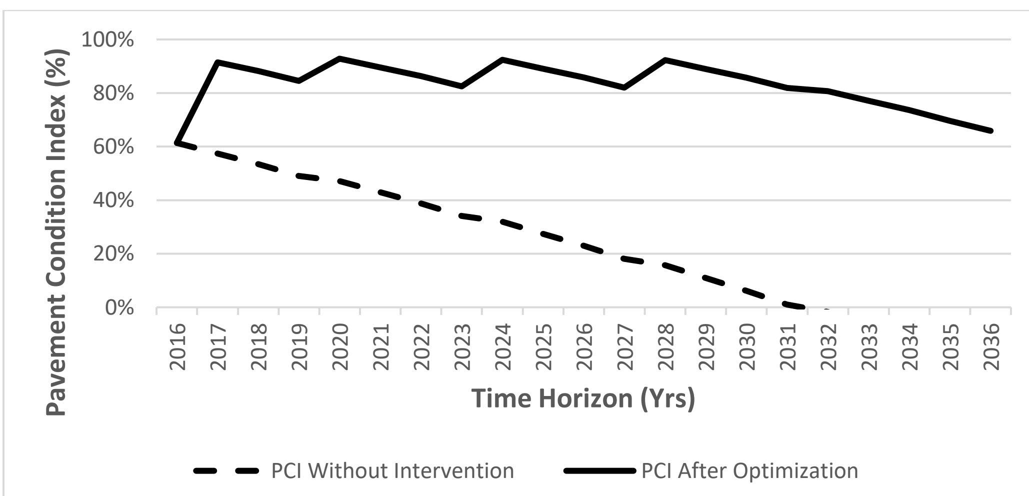
$\mathbf{RC}_{\boldsymbol{k_i}}$ is the recovery cost of corridor k at year i ($);

$\mathbf{RT}_{\boldsymbol{k_i}}$ is the recovery time of corridor k at year i (hrs).

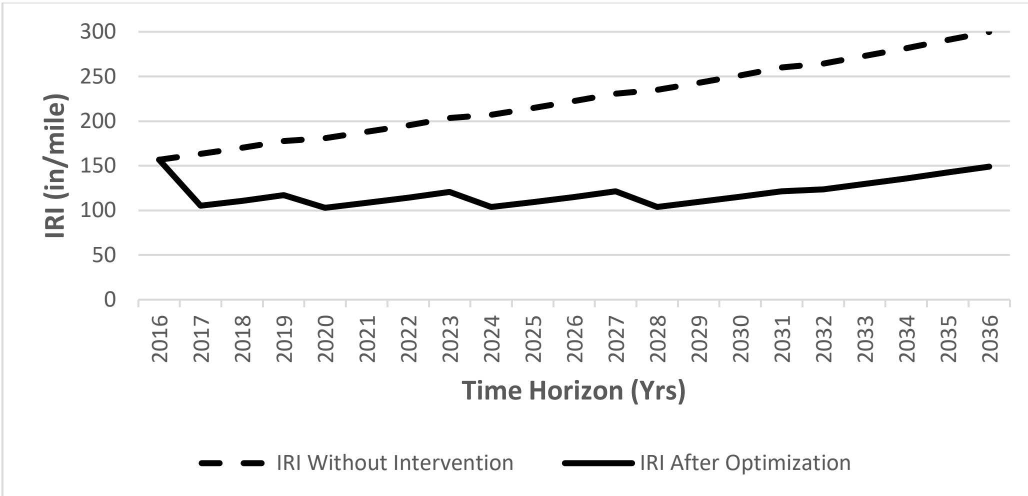
4.3. Preliminary Optimization Model

The proposed model was applied to the pilot case study through two different scenarios, with and without considering intervention actions, to understand better the effect of the Freeze-Thaw on the pavement condition and performance. The indicators were assessed for each corridor through the models explained earlier in the research methodology chapter. A sample of a corridor, corridor five, is demonstrated in Figure 4.1. It is evident that LOS, represented by the IRI, is the main threshold that reflects the need for intervention to keep the pavement corridor within the acceptable range. Four M&R intervention actions were undertaken during the study planning horizon in this corridor. All interventions were rehabilitation actions (Overlay and Deep patching). One action was carried out after the first year from the starting point due to the deteriorated initial conditions of that corridor. Other actions were planned at different times from the starting point due to aging and the Freeze-Thaw effect on the pavement deterioration.

Nevertheless, assuming no intervention actions were undertaken to maintain the pavement corridor under the desired thresholds, the deterioration of the corridor in terms of LOS and condition would be massive, and various complications will arise accordingly. Moreover, the end-users of that corridor will experience low service that will hinder residents of this area and other industries that might be using this corridor for transportation purposes. Furthermore, in case of sudden collapse, the failure likelihood of the corridor would increase, leaving the asset managers with no intervention options but undertaking the costly corridor reconstruction option due to the severe state of both LOS and condition.



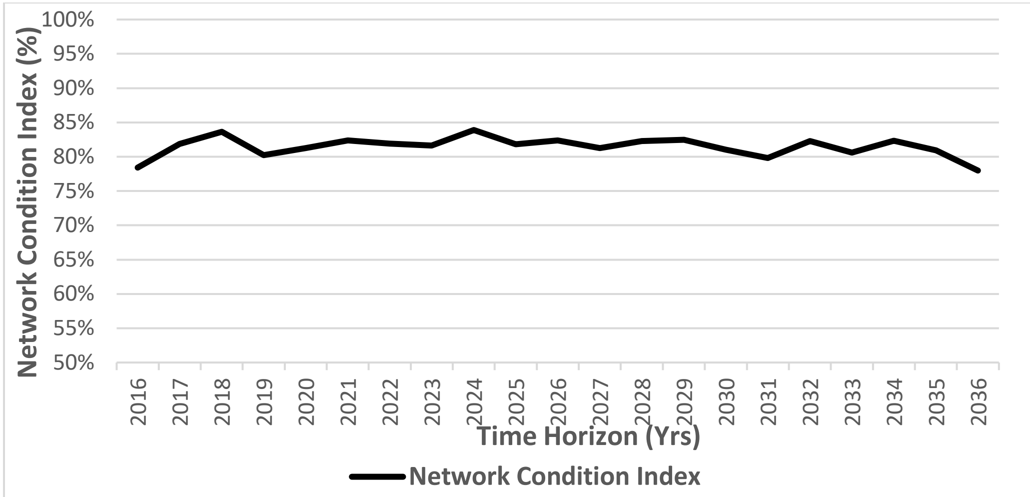
(a) Pavement Condition Index



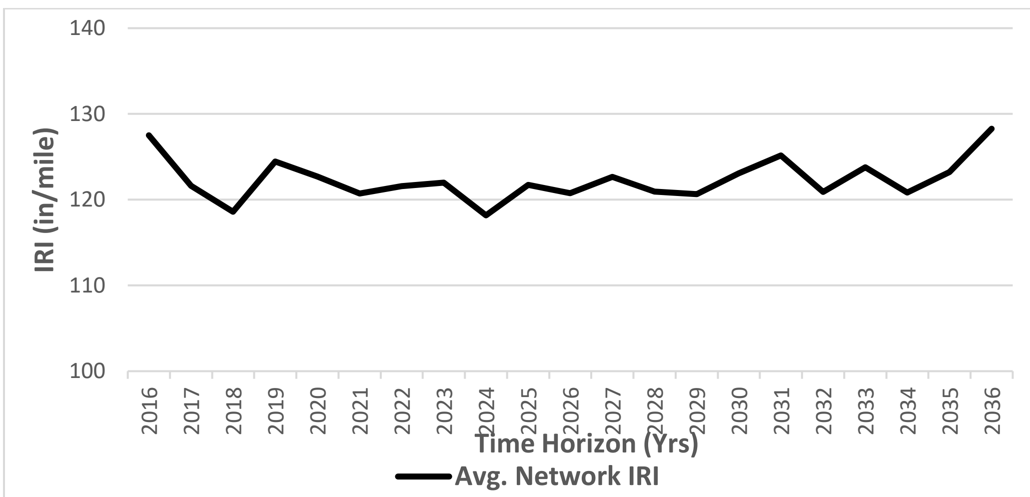
(b) Level of Service

Figure 4.1: Optimized vs. without interventions for corridor five (Section-level)

After applying the resilience assessment model on the network level, it was obvious that, without any M&R intervention actions taken through the study planning horizon, the pavement network would suffer from severe deterioration in LOS and condition and fall drastically below the acceptable thresholds. Nevertheless, the model showed promising results in terms of maintaining the pavement's resilience state to avoid any major collapse due to any sudden event based on LOS and PCI thresholds. The overall weighted average IRI fell within the acceptable ranges, reaching 122.35 in/mile. Besides, the overall pavement condition was rated good, with an overall weighted average PCI of 81.45%. Figure 4.2 displays the deterioration in PCI and IRI under annual Freeze-Thaw cycles and aging considering M&R intervention actions. Thus, the model is undertaking a trade-off analysis between undertaking M&R intervention actions to keep the network in an acceptable condition and LOS or saving money and time but deviating from the condition and LOS thresholds.



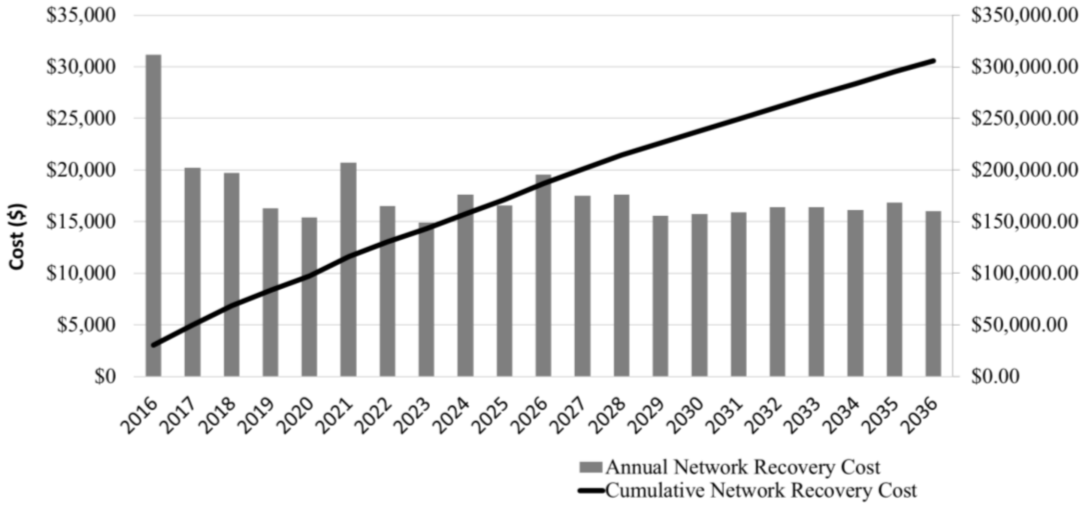
(a) Pavement Condition Index



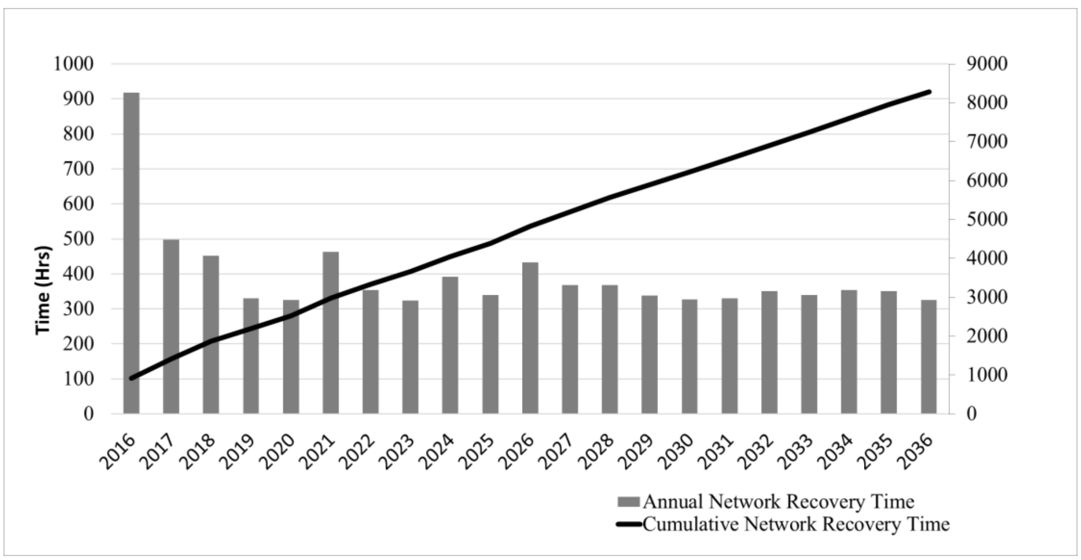
(b) Level of Service

Figure 4.2: Pavement condition and LOS under annual Freeze-Thaw cycles and aging (Network Level-Optimized)

To maintain an acceptable LOS for the corridors, a NPV value of $306k was allocated to undertake the M&R intervention actions throughout the 20-year life-cycle. In addition, the intervention actions resulted in a total of 8.27k man-hours of recovery time, as highlighted in Figure 4.3.



(a) Recovery cost



(b) Recovery time

Figure 4.3: Network annual and cumulative recovery cost and time

4.4. M&R Plan Results and Discussion

The results of the optimized intervention plan of the resilience assessment model are shown in Table 4.3. It could be noticed that the reconstruction activities would occur early throughout the study planning horizon. This was anticipated due to the LOS and condition thresholds that were preset to satisfy the resilience definition conditions where; the PCI and IRI restrained the model from falling below their thresholds, thus forcing it to undertake early M&R intervention actions. Moreover, as shown in Figure 4.4, fifty-seven minor rehabilitation actions and nine major rehabilitation actions were planned throughout the planning horizon to maintain the pavement network resilience state. Nevertheless, incorporating more disruption events on the pavement network would generate diverse M&R intervention plans with a different required budget to keep the network resilient against those disruptions.

Table 4.3: Optimized M&R intervention plan

Year	**Overlay**	**Deep Patching**	**Reconstruction**	**Number of Sections**
2016	-	Corridors 12,20	Corridors 11, 15, 18	5
2017	Corridors 2, 7, 13	Corridors 5, 17	-	5
2018	Corridors 3, 4	Corridor 6	-	3
2019	Corridor 1	-	-	1
2020	Corridors 5. 8, 20	-	-	3
2021	Corridors 10, 14	Corridors 16, 19	-	4
2022	Corridors 2, 4, 11, 18	-	-	4
2023	Corridors 6, 7, 17	-	-	3
2024	Corridors 1, 5, 15	Corridor 12	-	4
2025	Corridors 8, 13	-	-	2
2026	Corridors 3, 10, 14	Corridor 9	-	4
2027	Corridors 4, 18, 20	-	-	3
2028	Corridors 5, 11,19	-	-	3
2029	Corridors 1, 7, 9, 17	-	-	4
2030	Corridors 10, 13, 16	-	-	3
2031	Corridors 2, 6	-	-	2
2032	Corridors 1, 12, 15, 20	-	-	4
2033	Corridors 8, 16, 19	-	-	3
2034	Corridors 3, 4, 9, 14, 17	-	-	5
2035	Corridors 2, 11, 18	-	-	3
2036	Corridor 8	-	-	1
Number of Sections	57	9	3	69

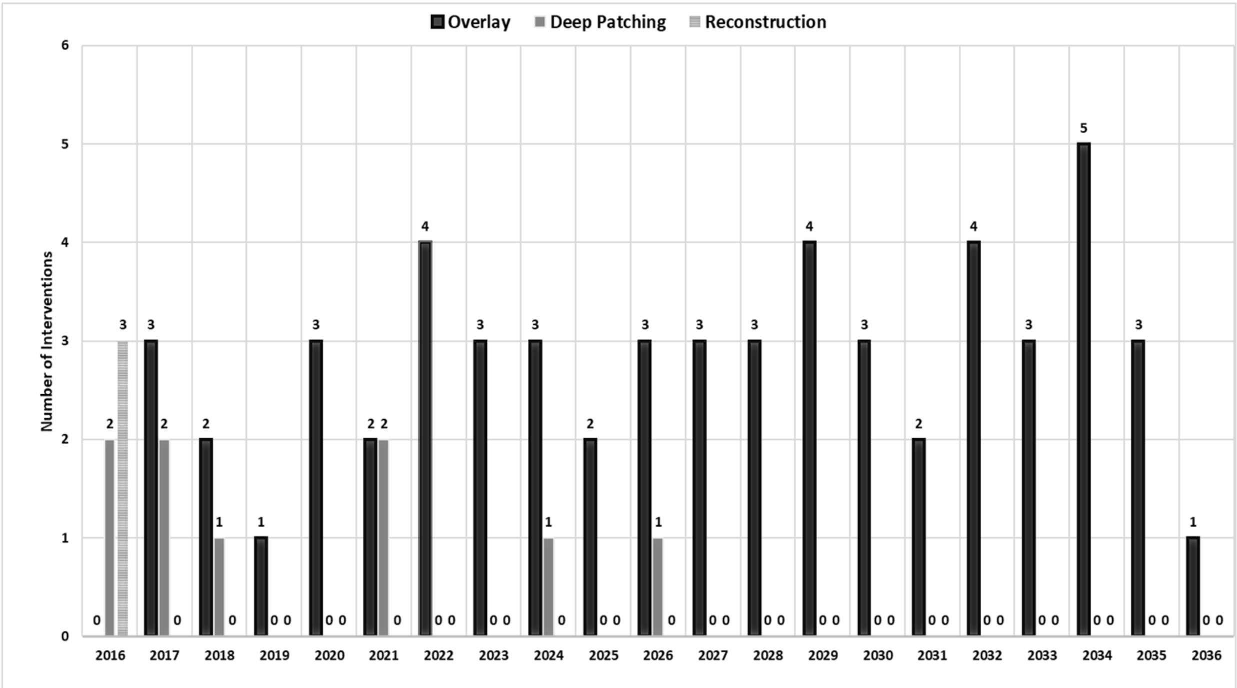


Figure 4.4: Optimized M&R intervention plan layout

4.5. PCA Model Implementation

The weights of the indicators were determined based on the proposed methodology as presented earlier in Section 3.5. After quantifying the resilience indicators and forecasting their values throughout the study planning horizon, each indicator was assigned a weight that reflects its contribution and importance to pavement resilience based on PCA analysis. After applying the weighted sum mean method to the indicators, each corridor's resilience index (RS) value shall be computed annually. Table 4.4 presents the corridor's average values for each resilience indicator, while Table 4.5 shows values after data standardization.

Table 4.4: Average resilience indicators values

Corridor ID#	*LOS (IRI)*	*Condition (PCI)*	*Redundancy*	*Recovery Time (hrs)*	*Recovery Cost ($)*
Corridor 1	113.72	86.50%	0.42	294.58	$ 13,871.00
Corridor 2	124.18	80.38%	0.44	256.96	$ 11,972.00
Corridor 3	127.94	78.18%	0.20	282.37	$ 13,439.00
Corridor 4	120.28	82.66%	0.75	566.50	$ 26,675.00
Corridor 5	119.81	82.93%	0.15	395.60	$ 17,480.00
Corridor 6	125.62	79.54%	0.80	600.48	$ 26,966.00
Corridor 7	120.35	82.62%	0.86	579.18	$ 27,636.00
Corridor 8	121.91	81.71%	0.54	309.68	$ 14,536.00
Corridor 9	122.45	81.39%	0.22	362.88	$ 16,296.00
Corridor 10	123.60	80.72%	0.62	349.69	$ 16,643.00
Corridor 11	117.96	84.02%	0.56	677.16	$ 28,272.00
Corridor 12	126.25	79.17%	0.05	341.70	$ 14,740.00
Corridor 13	126.36	79.11%	0.54	200.01	$ 9,492.00
Corridor 14	124.04	80.46%	0.50	303.38	$ 14,476.00
Corridor 15	122.05	81.63%	0.46	743.04	$ 31,218.00
Corridor 16	130.39	76.75%	0.22	230.64	$ 10,168.00
Corridor 17	120.86	82.32%	0.47	688.55	$ 30,765.00
Corridor 18	118.16	83.90%	0.73	295.61	$ 12,257.00
Corridor 19	128.61	77.79%	0.50	233.24	$ 10,353.00
Corridor 20	120.77	82.37%	1.00	565.95	$ 25,410.00

Table 4.5: Standardized resilience indicators values

Corridor ID#	*LOS (IRI)*	*Condition (PCI)*	*Redundancy*	*Recovery Time*	*Recovery Cost*
Corridor 1	100.00%	100.00%	38.95%	82.58%	20.16%
Corridor 2	37.25%	37.23%	41.05%	89.51%	11.41%
Corridor 3	14.70%	14.67%	15.79%	84.83%	18.17%
Corridor 4	60.65%	60.62%	73.68%	32.51%	79.09%
Corridor 5	63.47%	63.38%	10.53%	63.98%	36.77%
Corridor 6	28.61%	28.62%	78.95%	26.25%	80.43%
Corridor 7	60.23%	60.21%	85.26%	30.18%	83.51%
Corridor 8	50.87%	50.87%	51.58%	79.80%	23.22%
Corridor 9	47.63%	47.59%	17.89%	70.01%	31.32%
Corridor 10	40.73%	40.72%	60.00%	72.44%	32.91%
Corridor 11	74.57%	74.56%	53.68%	12.13%	86.44%
Corridor 12	24.84%	24.82%	0.00%	73.91%	24.16%
Corridor 13	24.18%	24.21%	51.58%	100.00%	0.00%
Corridor 14	38.09%	38.05%	47.37%	80.96%	22.94%
Corridor 15	50.03%	50.05%	43.16%	0.00%	100.00%
Corridor 16	0.00%	0.00%	17.89%	94.36%	3.11%
Corridor 17	57.17%	57.13%	44.21%	10.03%	97.91%
Corridor 18	73.37%	73.33%	71.58%	82.40%	12.73%
Corridor 19	10.68%	10.67%	47.37%	93.88%	3.96%
Corridor 20	57.71%	57.64%	100.00%	32.61%	73.27%

IBM SPSS® is utilized to perform PCA analysis on the resilience indicators data. Results of PCA analysis are shown in Tables 4.6 and 4.7. Kaiser-Meyer-Olkin Measure of sampling adequacy's value for our case study is 0.545, which is higher than 0.50 and therefore considered acceptable according to Kaiser (1974). This statistical test confirmed that no more data is needed to be collected or that eliminating some indicators isn't necessary; hence, PCA analysis is suitable for this data. Another essential test is Bartlett's test, which indicates whether the variables/indicators are unrelated and won't be appropriate to perceive data structure. The significance level for the test was less than 0.001 in our case study, which reflects a high significance level, and in return, PCA analysis might be suitable for the case study. As shown in Table 4.6, only components 1 and 2 have Eigenvalue >1, and thus only those components will be considered to calculate resilience indicators weights.

Table 4.6: Total variance illustration using PCA

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	3.101	62.019	62.019
2	1.139	22.787	84.805
3	.723	14.465	99.271
4	.036	.717	`99.987
5	.001	.013	100.000

Table 4.7: Squared cosines of the variables

Variables/Indicators	PC1	PC2
LOS (IRI)	0.673	0.326
Condition (PCI)	0.694	0.305
Redundancy	0.333	0.071
Recovery Time	0.729	0.168
Recovery Cost	0.672	0.269

The squared cosine values presented in Table 4.7 usually reflect the quality of data representation in the principal components. The closer the variables to the perimeter of the circle of correlations, the more significant contribution in the first and second components, as shown in Figure 4.5. Accordingly, to calculate the contributions of each variable to each principal component, each variable squared cosine was divided by the sum of the squared cosines for the same principal components, as shown in equation 4.1. Table 4.8 represents the contribution of each variable in each principal component.

$$w_{mn} = \frac{Cos_{mn}}{\sum_{n=1}^{n} Cos_{mn}} \qquad \text{Equation 4.1}$$

w_{mn} represents the weight for *n*th variable in the *m*th principal component,
Cos_{mn} represents the squared cosine value for the *n*th variable in the *m*th principal component.

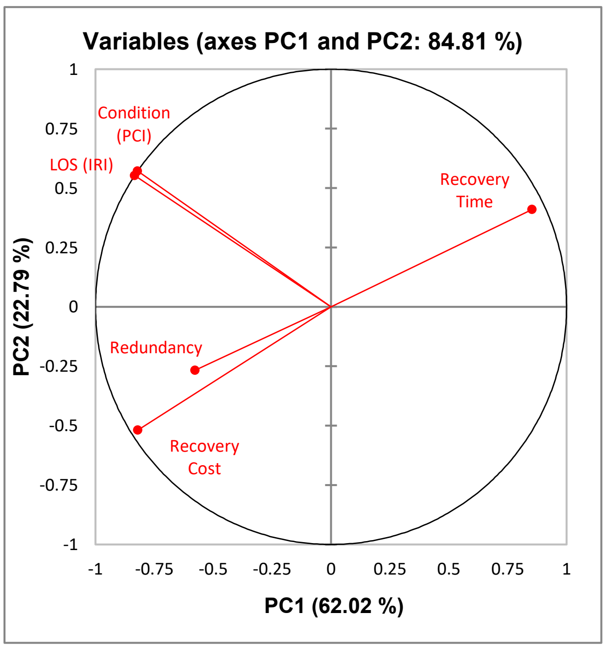


Figure 4.5: Circle of correlations

Table 4.8: Contribution of the variables %

Variables/Indicators	PC1	PC2
LOS (IRI)	0.217	0.286
Condition (PCI)	0.224	0.268
Redundancy	0.107	0.063
Recovery Time	0.235	0.147
Recovery Cost	0.217	0.236

According to the proposed method, substituting in Equation 3.25 leads to acquiring each indicator weight. The resulting weights are presented in Table 4.9.

Table 4.9: Resilience indicators derived weights

Variable/Indicator	*LOS*	*Condition*	*Redundancy*	*Recovery Time*	*Recovery Cost*
Weight	0.236	0.236	0.095	0.211	0.222

The obtained weights were based on average indicators values through the study planning horizon. The average RS for each corridor and the overall network resilience index shall be broadcasted based on earlier calculated resilience index weights and the correspondent network data obtained from the optimization model. LOS and condition had the same weight where their original data values were correlated while applying the proposed framework to the pavement network under study. Redundancy had low variability in the case study, which explains its minimal resulting weight value. The index shall reflect the resilience state of each corridor with respect to the proposed model. After substituting the weight values along with the average value of each resilience indicator for each corridor, after scaling, then the final RS values for each corridor would be obtained. A sample of the resulting RS values is shown in Table 4.10. From the RS values for each of the 5 sample corridors, corridor 1 has the highest RS value while corridor 3 has the least. The results align with the resilience-based assessment model output in Table 4.4 regarding the average resilience indicator values and the corresponding M&R intervention actions.

Table 4.10: Average RS values sample

Corridor ID#	*Corridor 1*	*Corridor 2*	*Corridor 3*	*Corridor 4*	*Corridor 5*
RS	0.73	0.43	0.30	0.60	0.53

4.6. Summary

The preliminary model implementation presented a case study that displayed the consequences of aging and Freeze-Thaw on pavement deterioration. Furthermore, the model results were promising in terms of maintaining pavement resiliency and selecting a near-optimal M&R intervention plan that meets the municipality's limitations in terms of condition, LOS, and cost. Therefore, the proposed pavement resilience assessment framework is beneficial for asset management experts where; M&R intervention plans would not only target enhancing or restoring pavement condition or LOS but also incorporate the implementation of proper recovery strategies for both regular and extreme events into the M&R intervention plan while taking the regular deterioration and aging effects into account. Moreover, integrating asset management and resilience is vital as infrastructure networks are suffering from aging and are vulnerable to many disruptive events, with limited budget available for undertaking the necessary intervention actions. Thus, a growing need is required to optimize the investment allocated to those assets, deliver the required LOS and avoid the long service cuts after any disruption.

Although the framework showed great potential, further development to include other extreme disruptive events through the study planning horizon is required. In addition, in the later stage of research, other limitations shall be addressed, such as; introducing detailed intervention actions for pavement maintenance, considering redundancy as an indicator for the available alternative routes for regular users, introducing both pavement surface condition and structural condition with two different parameters to serve as an additional asset condition related indicator, and apply the model with varying budget constraints to reflect the proposed concept's viability.

PCA was introduced as a novel technique to assign the weights for resilience indicators. Equation 3.25 was formulated based on understanding the PCA technique, each variable's contribution to the principal components, and their variability. The obtained weights would be further used to acquire average RS values for each corridor. Those values are dynamic and would change with input variations and maintenance and rehabilitation plans, matching with resiliency nature. The Resilience Index shall ease the decision-making process regarding pavement networks maintenance and rehabilitation and gives summarized insight about network resiliency with respect to the proposed resilience definition proposed by the author.

CHAPTER 5 – DATA COLLECTION AND UPDATED MODEL IMPLEMENTATION

5.1. Introduction

The preliminary case study was conducted to emphasize this study's primary objective, which is integrating resilience into the asset management concept. Nevertheless, all model elements are included and exhibited in the following case study to demonstrate the full potential of the proposed resilience definition and model. In Spring 2017, the Spring flood hit the Pierrefonds-Roxboro suburb in Montreal. A state of Emergency was declared, and hundreds of people were evacuated from their homes. Unfortunately, the flood struck unexpectedly, where such high-water levels had not been seen in 55 years, not to mention that the floodplain maps at the flooding time were outdated, returning to 1980 (Canadian Broadcasting Corporation, 2017, National Broadcasting Company, 2017). Outdated maps mean outdated information, which would eventually lead to unanticipated damages, and further disruption would occur through infrastructure networks without any planned response and maintenance strategies.

Data was collected through the City of Montréal open-source database (Données Québec, 2021). Data includes condition assessment results for designated road segments in the Montreal roads network. Both IRI and PCI values were assessed in three different years, 2010, 2015, and 2018. Appendices A, B, and C present the data acquired from the above database to fit the predefined case study. Pierrefonds Boulevard segments were the focus. The available data was evaluated while considering data availability in all three years. Accordingly, any segment with missing data in one of the three years will be omitted. Thirty-Nine corridors were established, forming a total of 7KM pavement network case study, as shown in Table 5.1.

Table 5.1: Pierrefonds Boulevard segments under-study

Corridor No.	*ID*	*Road Name*	*Length (m)*
1	4006216	de Pierrefonds boulevard	129
2	4006214	de Pierrefonds boulevard	128
3	4006221	de Pierrefonds boulevard	106
4	4006223	de Pierrefonds boulevard	214
5	1619908	de Pierrefonds boulevard	678
6	1619867	de Pierrefonds boulevard	123
7	4006211	de Pierrefonds boulevard	151
8	4006207	de Pierrefonds boulevard	188
9	4006208	de Pierrefonds boulevard	188
10	4007383	de Pierrefonds boulevard	129
11	4007387	de Pierrefonds boulevard	74
12	4006225	de Pierrefonds boulevard	331
13	4006224	de Pierrefonds boulevard	332
14	4006222	de Pierrefonds boulevard	321
15	4006213	de Pierrefonds boulevard	77
16	1619860	de Pierrefonds boulevard	187
17	1619832	de Pierrefonds boulevard	295
18	4001910	de Pierrefonds boulevard	201
19	4001909	de Pierrefonds boulevard	79
20	1620085	de Pierrefonds boulevard	510
21	4001908	de Pierrefonds boulevard	252
22	4001907	de Pierrefonds boulevard	255
23	1623317	de Pierrefonds boulevard	65
24	1620607	de Pierrefonds boulevard	203
25	1620991	de Pierrefonds boulevard	292
26	1620945	de Pierrefonds boulevard	261
27	1620664	de Pierrefonds boulevard	25
28	1620666	de Pierrefonds boulevard	213
29	1619984	de Pierrefonds boulevard	84
30	1619859	de Pierrefonds boulevard	68
31	1619611	de Pierrefonds boulevard	120
32	1619754	de Pierrefonds boulevard	147
33	1619616	de Pierrefonds boulevard	147
34	1619533	de Pierrefonds boulevard	381
35	1619615	de Pierrefonds boulevard	208
36	1619610	de Pierrefonds boulevard	255
37	1619608	de Pierrefonds boulevard	102
38	1619589	de Pierrefonds boulevard	93
39	1619614	de Pierrefonds boulevard	247

5.2. Model Development and Main Assumptions

This section presents in detail the main assumptions behind building the optimization model along with all sub-models based on section 3.3.

5.2.1. Asset-based indicators

PCI deterioration model introduced in Section 3.3 will be utilized to predict network corridors deterioration. The model proposed in Section 3.3 to predict IRI needs a considerable number of inputs regarding pavement condition, type of cracks that exist in the pavement, and additional information regarding subgrade properties. Due to the unavailability of these inputs in the network under study, the IRI deterioration model would be extracted from the available IRI data values to match and emulate the existing deterioration in the case study. The available IRI data represents the existing deterioration for pavement corridors in the case study and incorporates maintenance and rehabilitation actions' effect on IRI. The method to extract IRI deterioration was achieved by utilizing the available PCI values in the pavement condition deterioration model to calculate an approximate equivalent age for that deterioration value. Several corridors and corresponding PCI values were analyzed, reflecting different PCI values and thus acquiring their consequent age. Figure 5.1 presents the resulting deterioration model. The equation formulation for the extracted model is as follows:

$$IRI_i = 0.011i^2 - 0.0434i + 1.98 \qquad \text{Equation 5.1}$$

where;

$\boldsymbol{IRI_i}$ is the anticipated IRI at year i; **i** is the year counter (%);

The extracted IRI deterioration from the case study dataset includes an error. It includes the effect of the maintenance and rehabilitation actions taken through the period where this dataset was recorded. Nevertheless, this model will serve as an acceptable benchmark in this study. On the other hand, Equation 2.7 will be utilized to forecast IRI values considering aging, traffic loads and growth, climatic effects, and its expected changes through the study time horizon. Based on the highest degradation trend of the IRI between both methods, IRI deterioration shall be forecasted, including the frequent climatic impacts.

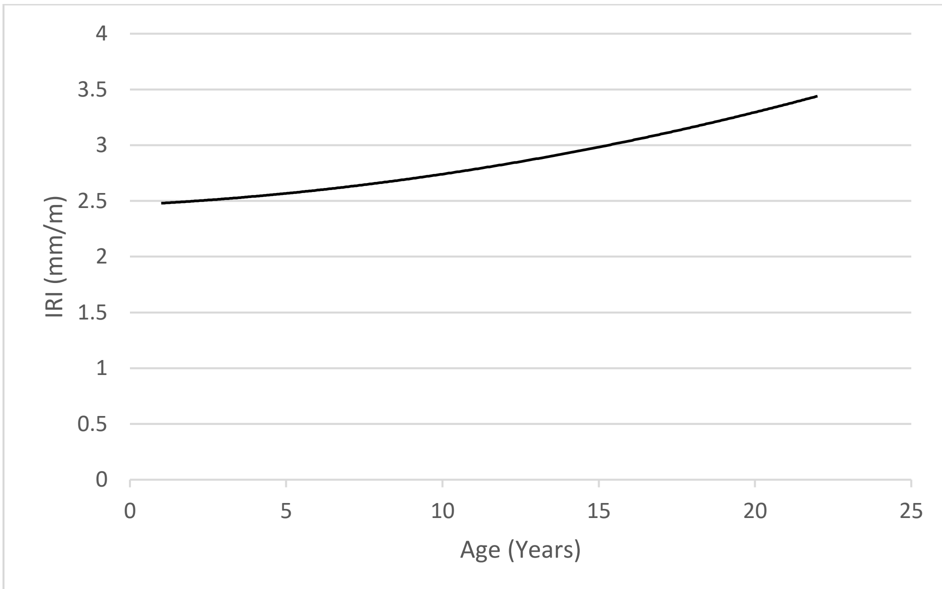


Figure 5.1: IRI Deterioration prediction model based on the dataset

Equation 2.7 relies on the availability of projected climatic data through the study time horizon while considering the anticipated traffic growth. Figure 5.2 presents the projected change in the Freezing Index, Freeze-Thaw cycles, Precipitation and Cooling Index in the Montreal region, considering climate change's adverse effects. The ESAL is expected to have a 25% increase for flexible arterial roads in the Montreal region during the study time horizon (Amin et al., 2015; Zhong, 2017). The estimated average value for each input is presented in Table 5.2.

Table 5.2: Average values for input parameters in Equation 2.7

Input parameter	Estimated values
PERCIP (mm)	1050
FI (°C - days)	790
CI (°C - days)	335
FTC	60
ESAL per year	162,000
SN	5

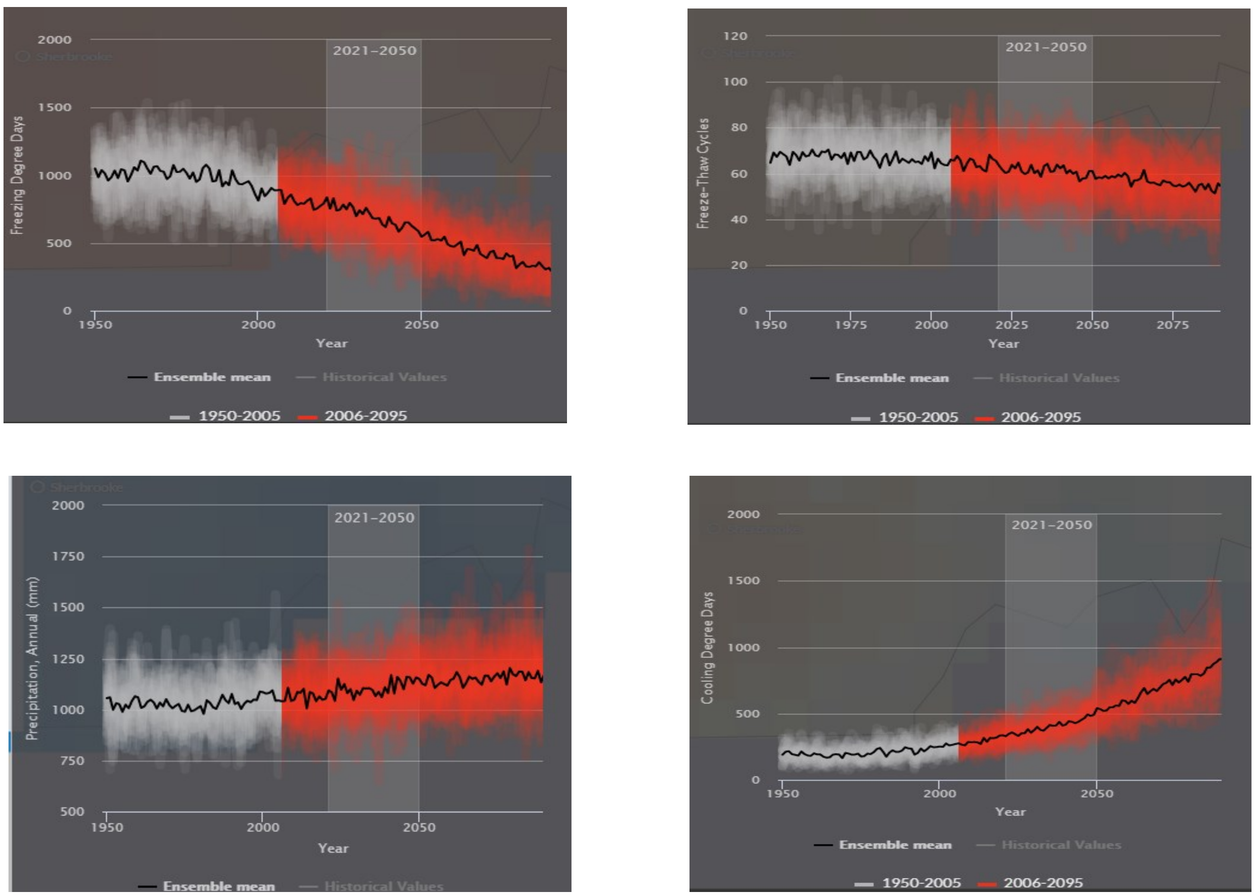


Figure 5.2: Projected change in FI, FTC, PERCIP, and CI values in the Montreal region (Climate Atlas of Canada, 2021).

IRI thresholds will be utilized based on Transportation Association of Canada (TAC) 2012 endorsements, as presented in Table 5.3. Around 50% adjustment was made for those values to account for highway non-highway differences where the highways typically have more strict thresholds than non-highway pavement networks. IRI threshold values match the case study IRI condition rating system and values (Bakhtiari & Officer, 2020; Ahmed et al., 2021).

Table 5.3: IRI values classification

Road Quality, IRI rating	**TAC 2012 IRI Thresholds (mm/m)**	**IRI Thresholds (mm/m)**
Very Good	< 1.0	< 1.50
Good	1.00 – 1.75	1.50 – 2.70
Fair	1.75 – 2.80	2.70 – 4.20
Poor	2.80 – 3.75	4.20 – 5.20
Very Poor	> 3.75	> 5.20

Redundancy will be calculated based on Section 3.3.2. RI will be calculated for each pavement corridor based on the following assumption. Equation 3.6 calculates nodes redundancy for the pavement network. Each link consists of two nodes; therefore, link redundancy will equal the least RI value for every two nodes forming each pavement link. Links' inflow and outflow are assumed to be identical for ease of calculations, and the relative flow of each link is given an AADT value based on the road classification for each link, as shown in Table 5.4. The RI value for each corridor was then calculated and is presented in Table 5.5.

Table 5.4: Case study segments AADT values based on road type classification (City of Toronto, 2013; Maadani et al., 2021)

Road Name	*Road Type*	*AADT*
Pierrefonds Boulevard, Saint-Charles Boulevard, Sain-Jean Boulevard	Major Arterials	5,000
Jacques-Bizard Boulevard, Du Chateau-Pierrefonds Avenue	Minor Arterials	2,500
Westpark Boulevard, Rue Perron, Rue Fredmir	Collectors	1,500
Rest of the network corridors	Locals	500

Table 5.5: RI values for each segment in the case study classification

No.	*Road Name*	*From*	*To*	*RI(Link)*
1	de Pierrefonds boulevard	Dresden rue	Westpark boulevard	0.775
2	de Pierrefonds boulevard	Dresden rue	Westpark boulevard	0.775
3	de Pierrefonds boulevard	Bastien rue	Coulon rue	0.775
4	de Pierrefonds boulevard	Coulon rue	Perron rue	0.775
5	de Pierrefonds boulevard	Paiement rue	Sainte-Anne rue	0.720
6	de Pierrefonds boulevard	Sainte-Anne rue	Becket rue	0.720
7	de Pierrefonds boulevard	Saint-Barnabas rue	Dresden rue	0.775
8	de Pierrefonds boulevard	rue Athéna rue	Saint-Barnabas rue	0.775
9	de Pierrefonds boulevard	rue Athéna	Saint-Barnabas rue	0.775
10	de Pierrefonds boulevard	avenue du Chateau-Pierrefonds avenue	Winnie-Wakefield rue	0.720
11	de Pierrefonds boulevard	Winnie-Wakefield rue	Paul-Pouliot rue	0.775
12	de Pierrefonds boulevard	Perron rue	Fredmir rue	0.890
13	de Pierrefonds boulevard	Perron rue	Fredmir rue	0.890
14	de Pierrefonds boulevard	Bastien rue	Perron rue	0.775
15	de Pierrefonds boulevard	Saint-Barnabas rue	Dresden rue	0.775
16	de Pierrefonds boulevard	Richelieu terrasse	Forbes rue	0.775
17	de Pierrefonds boulevard	Forbes rue	Saint-Charles boulevard	0.775
18	de Pierrefonds boulevard	Saint-Pierre rue	de Pierrefonds boulevard	0.720
19	de Pierrefonds boulevard	de Pierrefonds boulevard	Jacques-Bizard boulevard	0.959
20	de Pierrefonds boulevard	de Pierrefonds boulevard	Harry-Worth rue	0.720
21	de Pierrefonds boulevard	Harry-Worth rue	Esther-Blondin rue	0.720
22	de Pierrefonds boulevard	Esther-Blondin rue	Saint-Pierre rue	0.720
23	de Pierrefonds boulevard	Saint-Jean boulevard	de Pierrefonds boulevard	1.000

No.	Road Name	From	To	RI(Link)
24	de Pierrefonds boulevard	Rene-emard rue	Saint-Jean boulevard	0.720
25	de Pierrefonds boulevard	de Pierrefonds boulevard	Belleville rue	0.775
26	de Pierrefonds boulevard	Belleville rue	Fox rue	0.775
27	de Pierrefonds boulevard	Fox rue	Aragon rue	0.775
28	de Pierrefonds boulevard	Aragon rue	Richmond rue	0.720
29	de Pierrefonds boulevard	de Pierrefonds boulevard	Jacques-Bizard boulevard	0.959
30	de Pierrefonds boulevard	Becket rue	Pierrefonds boulevard	0.775
31	de Pierrefonds boulevard	Blaignier rue	Guillaume rue	0.618
32	de Pierrefonds boulevard	Saint-Charles boulevard	Blaignier rue	0.775
33	de Pierrefonds boulevard	Dorsi rue	de Riva-Bella rue	0.720
34	de Pierrefonds boulevard	de Riva-Bella rue	avenue du Chateau-Pierrefonds	0.720
35	de Pierrefonds boulevard	des Cageux rue	Dorsi rue	0.720
36	de Pierrefonds boulevard	Guillaume rue	rue Geneviève	0.720
37	de Pierrefonds boulevard	rue Geneviève	de Nanterre rue	0.720
38	de Pierrefonds boulevard	de Nanterre rue	Grier rue	0.720
39	de Pierrefonds boulevard	Grier rue	des Cageux rue	0.720

5.2.2. Disruption based indicators

Two main disruptive events are considered; Freeze-thaw as a non-extreme event and flooding as an extreme event. While the degradation of the surface condition due to Freeze-Thaw is already implied in Equation 2.7, the yearly degradation in pavement resilient modulus due to Freeze-Thaw cycles would be reflected in its structural condition, as shown in Equation 3.8.

Montreal lies in a zero-to-20-year flood zone, which means there is a +5% likelihood of a yearly flooding event. The flooding effect on IRI is calculated using Equation 3.9. Based on the available flooding data about the 2017 flooding event that destructively hit several parts of Quebec and Ontario, several assumptions were made to simulate the flooding event in our case study. First, flooding is assumed to occur once through the study planning horizon. Second, the average flooding duration and depth in the affected corridors are considered to be seven days and 45 centimeters, respectively. The previous assumption was based on different news articles and multiple descriptions and images of the flooded parts of Pierrefonds Boulevard. Third, the flood depth was computed relative to the submerged fire hydrants. Finally, the percentage increase of IRI due to flooding is assumed to be the reduction percentage in PCI.

On the other hand, and based on the literature review in Section 3.3.3, the deterioration in the structural condition for the fully submerged pavement section is assumed to be in the form of a reduction value of 50% from its structural condition before the flooding event. Figures 5.3 to 5.6 present the flooding maps for the Greater Montreal area, Pierrefonds-Roxboro borough, the updated flooding zone, and the segments in the flooding zone along Pierrefonds Boulevard. Based on the flooding maps presented in this section, corridors from 19 to 24 and 27 to 29 shall undergo flooding adverse effects on their surface and structural condition, as mentioned previously.

Figure 5.3: Flooding map for Greater Montreal area (Centre d'expertise hydrique du Québec, 2021)

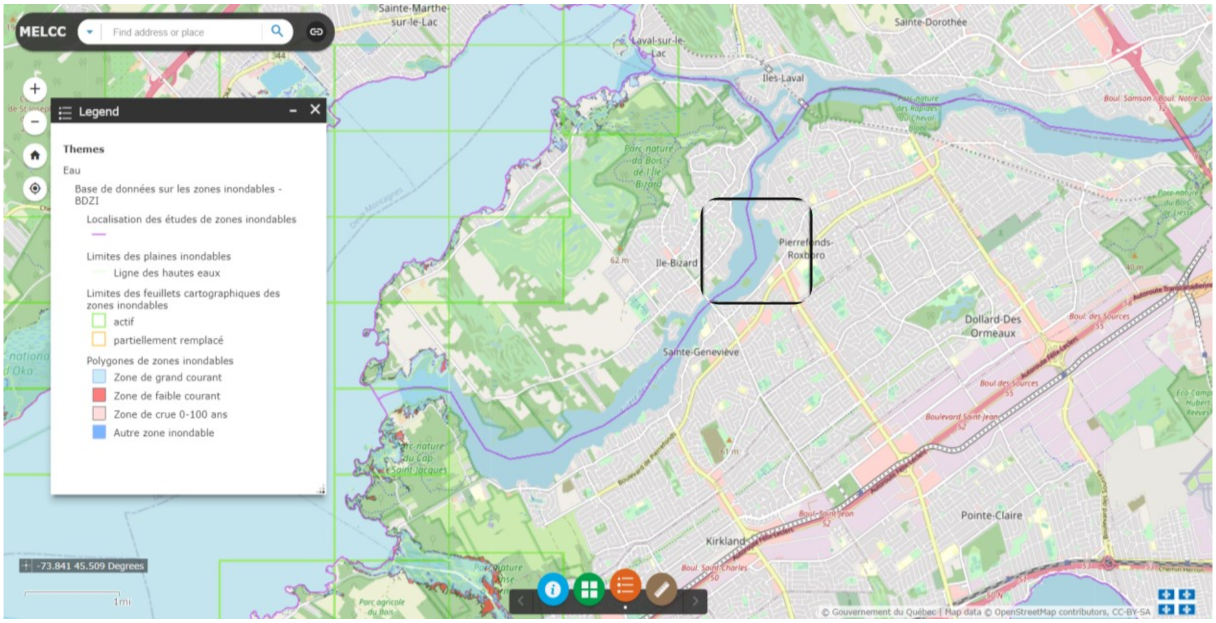


Figure 5.4: Pierrefonds Boulevard flooding zone (Centre d'expertise hydrique du Québec, 2021)

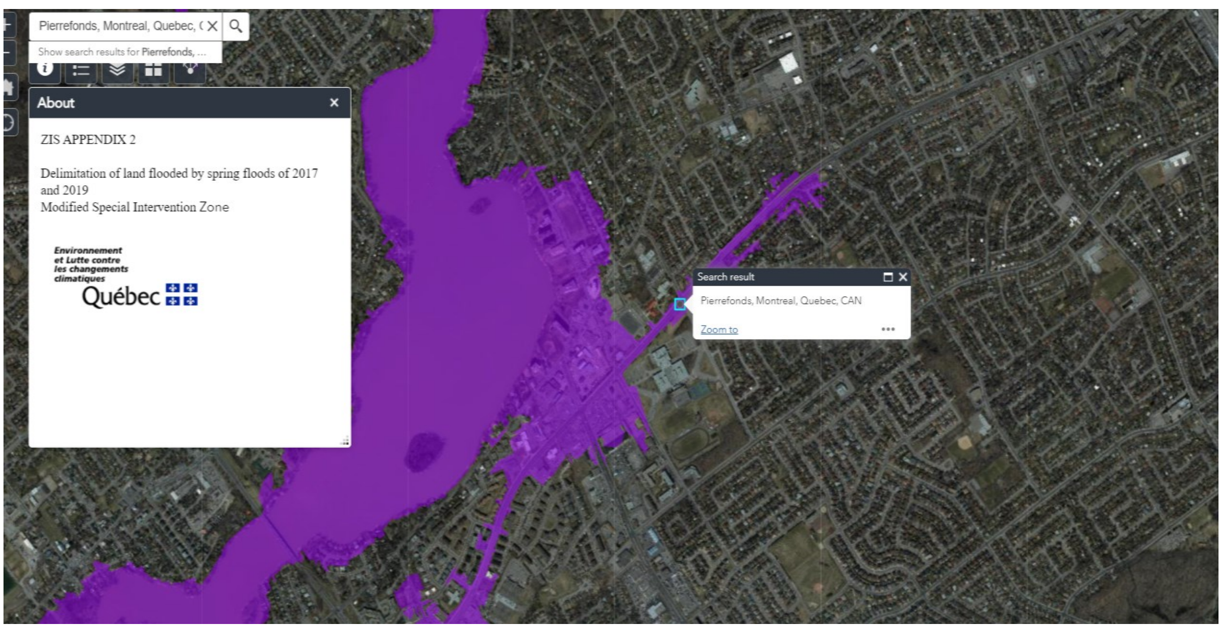


Figure 5.5: Pierrefonds Boulevard segments in the flooding zone (Centre d'expertise hydrique du Québec, 2021)

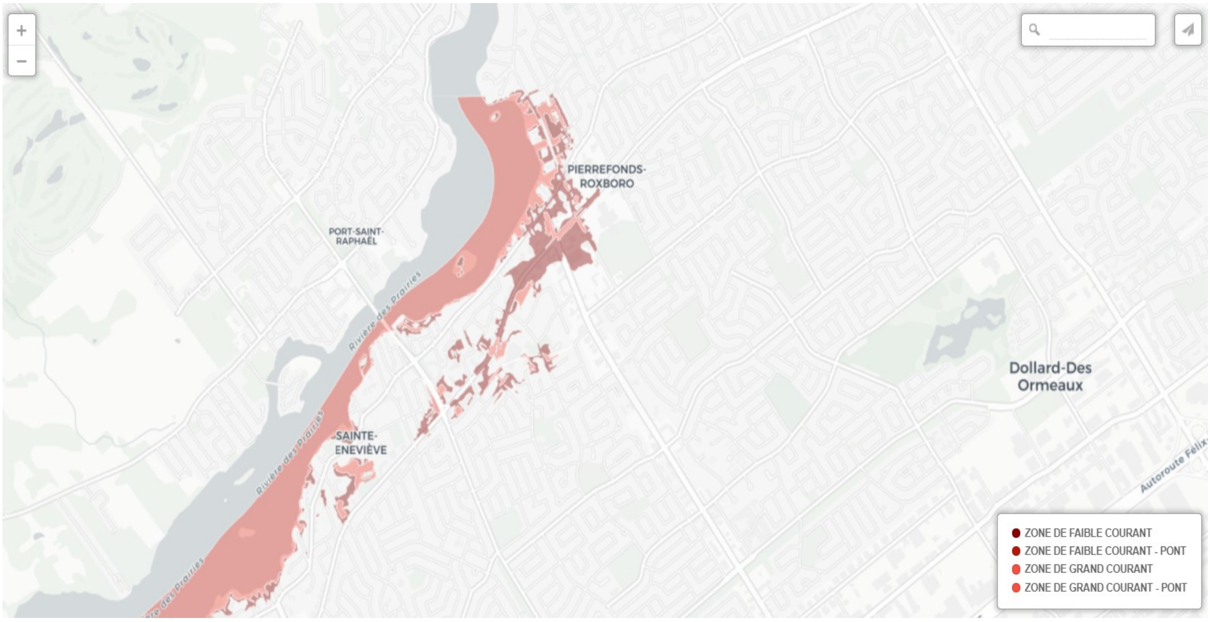


Figure 5.6: Pierrefonds-Roxboro flood zones (Carto, 2021)

Based on the flooding map in Figure 5.6 and the affected network corridors, the flood is categorized as a 100-year flood with a probability of 1% each year. For the case study planning horizon of 20 years, the expected probability of occurrence will be calculated as shown in Equation 5.2.

$$P_i = 1 - (1 - P_o)^i \qquad \text{Equation 5.2}$$

where;

$\boldsymbol{P_i}$ is the probability that the flooding event will occur in i years (%),

$\boldsymbol{P_o}$ is the yearly average flood probability (%).

The previously mentioned sections are only affected by the 100-year flooding event and are not affected by the regular zero-to-20-year flood. Nevertheless, from Equation 5.2, there is a probability of 18.2% that a 100-year flood will hit once those sections through the case study planning horizon. Consequently, it is safe to assume that the flood will occur in 2017 to match the case study real scenario and reduce optimization model complexity. Figure 5.7 represents the probability distribution that the flood would hit at least once through a certain period of time. It is crucial to point out that only river flooding and its effect on the nearby pavement network corridors are considered. In contrast, rainfall floodings and the role of the pavement drainage system are not considered.

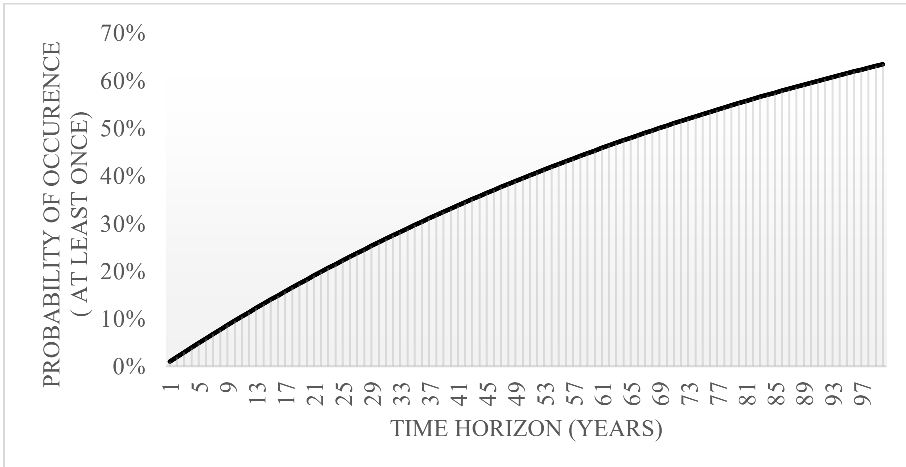


Figure 5.7: Probability distribution that the flood would hit at least once through a certain period

5.2.3. Recovery based indicators

Maintaining roads in Montreal cost the city an average of $27.58 per meter in 2017. This cost included maintenance, rehabilitation, and cleaning works, excluding winter works such as snow removal. Despite those expenditures, which made the roads of Montreal the most expensive roads to maintain around Canada, 70% of Montreal roads were in fair condition or worse (Montreal Gazette, 2017). It is essential to mention that there was not much traffic surge that could cause such deterioration and condition. In 2019, 51% of the Québec highway system's road conditions were recorded as fair or worse. Accordingly, around 83% of the total investments of $28.3 billion in the current road network infrastructure portfolio in Québec is allocated for maintenance, rehabilitation, and restoration of that portfolio (Chetverikov, 2021).

Table 3.4 is revised based on Figure 5.8 and is updated accordingly, as shown in Table 5.6. Figure 5.8 presents the applicability range of each maintenance category and intervention action.

Those ranges reflect the condition at which the type of intervention should be applied. It is essential to mention that the exact intervention action to be used in each maintenance category depends on the type of distress and deterioration that mainly exists in the pavement corridor under investigation (Babashamsi et al., 2022). Though this is not part of this research, our main target in this section is to predict a network-level maintenance and rehabilitation plan. Routine maintenance is assumed and recommended to be used no more than an average of five times during the pavement life cycle. It is combined with different preventive actions, which would be cost-ineffective if used beyond that number of times. Minor rehabilitation activities are performed as long as the pavement structure is sufficiently strong with no limitation for their recurrence during the pavement's life cycle. It is recommended to perform the reconstruction when pavement age exceeds ten years from its initial construction to serve as an economical option when deemed mandatory. It is essential to point out that reconstruction in this study focuses on returning that pavement condition to its original state.

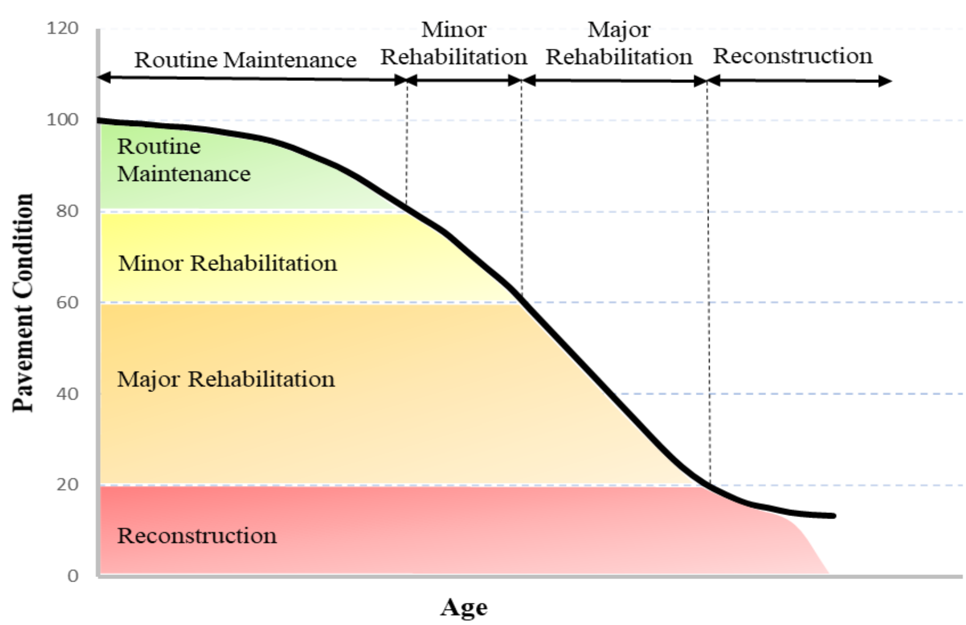


Figure 5.8: M&R Intervention actions applicability range versus each intervention category

Table 5.6: Revised Intervention Actions (City of Toronto, 2013; Patel and Ruparathna, 2021)

Maintenance actions	**Notation in 2nd level decision variables**	**PCI application range**	**Impact on PCI (%)**	**Recovery Time (hr/unit)**	**Recovery Cost ($/unit)**	**Estimated applicability**
Routine Maintenance (e.g., Crack filling, sealing, etc.)	-	80%-90%	-	0.30	10/m	20%
Minor Rehabilitation (Mill Overlay HMA)	1	60% - 80%	1.125 PCI_{x-1}	0.45	15/m^2	100%
Major Rehabilitation (Deep Patching)	2	20% - 60%	90% PCI_{in}	0.60	45/m^2	50%
Reconstruction	3	0% - 20%	100% PCI_{in}	1	130/m^2	100%

Unit costs in Table 5.6 will be later multiplied by a percentage (Estimated applicability) of each corridor length or area to obtain maintenance and rehabilitation costs when required throughout the planning time horizon. Each municipality or province typically sets its discount rate to adjust for interest rates and inflation in the future. Therefore, this study will use a 5% discount rate to match the discount rates for the province of Ontario and Québec (Alaloul et al., 2021, Patel & Ruparathna, 2021). It is worth mentioning that these costs will be increased by 10% for routine maintenance and 25% for other types of intervention to account for the requisite administrative costs. The mathematical formulation of the impact of the maintenance actions, aka decisions variables, is displayed through Equations 5.3 to 5.5.

$$PCI_{ik} = \begin{bmatrix} Do\ Nothing & 0.033i^2 - 2.688i + PCI_{in} \\ Minor\ Rehab. & (1.125)PCI_{x-1} \\ Major\ Rehab. & (0.90)PCI_{in} \\ Reconstrcution & PCI_{in} \end{bmatrix} \quad \text{Equation 5.3}$$

$$NCI_i = \sum_{i=1}^{n}[W_k * PCI_{ik}] \quad \text{Equation 5.4}$$

$$NCI = \overline{NCI_i} \quad \text{Equation 5.5}$$

where;

$\boldsymbol{PCI_{ik}}$ **i**s the pavement condition index at year i for corridor k,

$\boldsymbol{PCI_{in}}$ is the initial pavement condition,

$\boldsymbol{NCI_{i}}$ is pavement network average condition at year i,

$\boldsymbol{NCI}$ is pavement network average condition.

The effect of maintenance actions on the structural condition of pavement will be reflected as an improvement percentage in its structural condition. Since the data available for the case study does not provide any means of calculations for structural conditions indices, the improvement percentage will be applied to the pavement resilience index to reflect its structural condition. Rebuilding the whole pavement structure, known as reconstruction, shall bring its structural condition to its initial value unless the reconstruction process involves retrofit. Major rehabilitation activities, including rebuilding or replacing pavement layers components, shall restore pavement structural condition to 90% of its initial condition. It is worth mentioning that the application of any rehabilitation activities depends on the structural condition of its layers (Alaloul et al., 2021; Patel & Ruparathna, 2021). Practically, using surface condition applicability thresholds, as shown before in Table 5.6, shall function likewise in this model.

5.3. Core Optimization Model Development

Evolver^{TM} Version 8.1 was utilized with an advanced Excel^{TM} spreadsheet modeling to develop the optimization model, which embodies the author's resilience definition. Thus, the objective of the optimization model is to maximize the LOS of the case study pavement network throughout the planning horizon. The same concept used in section 3.3 to model the decision variables were used in this model. Decision variables were functioning on two levels. The first level was formulated using binary coding rules, where "0" represents the "Do Nothing" option and

“1” represents the existence of an M&R intervention action. Given the fact that three intervention actions were considered in this study to indicate the different maintenance actions that need to be undertaken in other condition states, a second level was formulated to select the appropriate intervention action based on the condition, and LOS application ranges defined earlier in Table 5.6. Thus, a “1” in the first level of decision variables might represent either “1” or “2” or “3” in the second level, which reflects the most appropriate intervention action, depending on the PCI application ranges.

Finally, nine constraints are set to ensure that the chosen M&R intervention scenarios are valid. Similar to the first level of decision variables, the constraints are modeled through binary coding rules, where “0” represents meeting the constraint, and “1” represents failing to meet the constraint. The five constraints are as follows: (1) annual recovery cost should not exceed the available annual budget, (2) annual recovery time should not exceed the total number of annual available resources, represented by working hours, (3) PCI of any section at any point of time throughout the planning horizon should meet the minimal condition threshold 20%, (4) the average network PCI at any year throughout the planning horizon should meet the minimal condition threshold 60%, (5) IRI of any section at any point of time throughout the planning horizon should meet the LOS threshold 5.2mm/m, (6) the average network at any year IRI throughout the planning horizon should meet the LOS threshold 2.7mm/m, and (7) number of annual interventions should not exceed 20% of the total number of sections in the network to avoid extreme service disruption (8) number of successive routine maintenance activities (Do Nothing) per corridor should not exceed five throughout the planning horizon (9) number of reconstruction activities should not exceed two per corridor throughout the planning horizon. The mathematical formulations of the constraints are mathematically formulated as shown in Equations 5.6 through 5.15.

Minimize overall weighted average network IRI_i;

$\frac{1}{s} \sum_{k=1}^{s} \sum_{i=1}^{T} \mathrm{W_k} * IRI_{ik}$ Equation 5.6

Subject to the following constraints:

$\mathrm{N}RC_i \leq \text{Annual budget}$ Equation 5.7

$NRT_i \leq \text{Annual working hours}$ Equation 5.8

$PCI_{ik} \geq PCI_{th}$ Equation 5.9

$\mathrm{PCI}_{Net_i} \geq PCI_{th}$ Equation 5.10

$IRI_{ik} \leq IRI_{th}$ Equation 5.11

$IRI_{Net_i} \leq IRI_{th}$ Equation 5.12

$\sum_{k=1}^{s} X_{i_k} \leq 20\% * \mathrm{s}$ Equation 5.13

$\sum_{t=i}^{i+6} X_{i_k} \leq 5$; where k=1, 2, 3,… or k, and X=0 Equation 5.14

$\sum_{t=1}^{T} X_{i_k} \leq 2$; where k=1, 2, 3,… or k, and X=3 Equation 5.15

$$\textbf{Decision variables} = \begin{bmatrix} X_{i_k} & \cdots & X_{T_k} \\ \vdots & \ddots & \vdots \\ X_{i_s} & \cdots & X_{T_s} \end{bmatrix}$$

where;

$\boldsymbol{IRI_{ik}}$ is the international roughness index at year i for corridor k (m/km),

$\boldsymbol{W_k}$ is the weight of corridor k where $W_k = \frac{L_k}{L_{net}}$ (%),

$\boldsymbol{NRC_i}$ is the network recovery cost at year i ($),

$\boldsymbol{NRT_i}$ is the network recovery time at year i (hrs),

$\boldsymbol{PCI_{ik}}$ is the pavement condition index at year i for corridor k (%),

$\mathbf{PCI}_{Net_i}$ is the weighted average network condition at year i (%)

PCI_{th} is the minimally acceptable pavement condition index (%),

IRI_{ik} is the international roughness index at year i for corridor k (mm/m),

$\mathbf{IRI}_{Net_i}$ is the weighted average network international roughness index at year i (mm/m),

IRI_{th} is the international roughness index predefined threshold (mm/m),

X_{i_k} is the intervention action for corridor k at year i (e.g., “0” for “Do Nothing and “1” for “Intervention action”),

k is the pavement corridors counter,

s is the total number of corridors and,

T is the planning horizon.

Equations 5.17 and 5.18 characterize those parameters calculations on the network level to distinguish between the overall weighted average network LOS, condition, and recovery indicators.

$$\mathrm{PCI}_{Net_i} \text{or } \mathrm{IRI}_{Net_i} = \sum_{k=1}^{s} \frac{(L_k * PCI_{ik} \text{ or } IRI_{ik})}{L_{net}} \qquad \text{Equation 5.17}$$

$$\mathrm{NRC}_i \text{ or } \mathrm{NRT}_i = \sum_{k=1}^{s} \mathrm{RC}_{ik} \text{ or } \mathrm{RT}_{ik} \qquad \text{Equation 5.18}$$

where;

$\mathbf{L}_k$ represents the length of corridor k (m),

L_{net} is the total length of the sections within the network (m),

$\mathbf{NRC}_i$ is the recovery cost of the network at year i ($),

$\mathbf{NRT}_i$ is the recovery time of the network at year i (hrs),

$\mathbf{RC}_{ik}$ is the recovery cost of corridor k at year i ($),

$\mathbf{RT}_{ik}$ is the recovery time of corridor k at year i (hrs).

For the City of Montreal decision-makers management level, the prime target is to reduce costs and maintain an acceptable LOS for end users. Thus, it is crucial to utilize the proposed optimization model for a second scenario where the objective function targets minimizing the network LCC as follows:

Minimize overall average network LCC subject to the same constraints from the first scenario.

$$\sum_{i=1}^{T}\left[\sum_{k=1}^{s}[RC_{ik}] * (1 + in)^{I}\right]$$

where;

$RC_{ik} = [X_{ik} * \ RUC_x * \ L_k]$ Equation 5.19

$\boldsymbol{RC_{ik}}$ is the rehabilitation/Recover cost of corridor k at year i,

$\boldsymbol{X_{ik}}$ is a binary decision variable with "0" representing the "Do nothing" option and "1" representing the "Rehabilitation/Recovery" action,

$\boldsymbol{RUC_x}$ is the recovery unit cost of decision variable X,

$\boldsymbol{L_k}$ is corridor length,

$\boldsymbol{I}$ is the cash flow time

5.4. Results and Model Analysis

The proposed model generates the mathematical description for the author's resilience definition via utilizing optimization as an analytical approach for the predefined model. The optimization characteristics could be summarized as follows: crossover rate: 90%, mutation rate: 10%, and stoppage criteria: progress-based. Evolver™ optimization summary for the proposed model is shown in Figure 5.9. Figure 5.9 presents the positive change in IRI value, on the vertical axis, with the conducted trials on the horizontal axis.

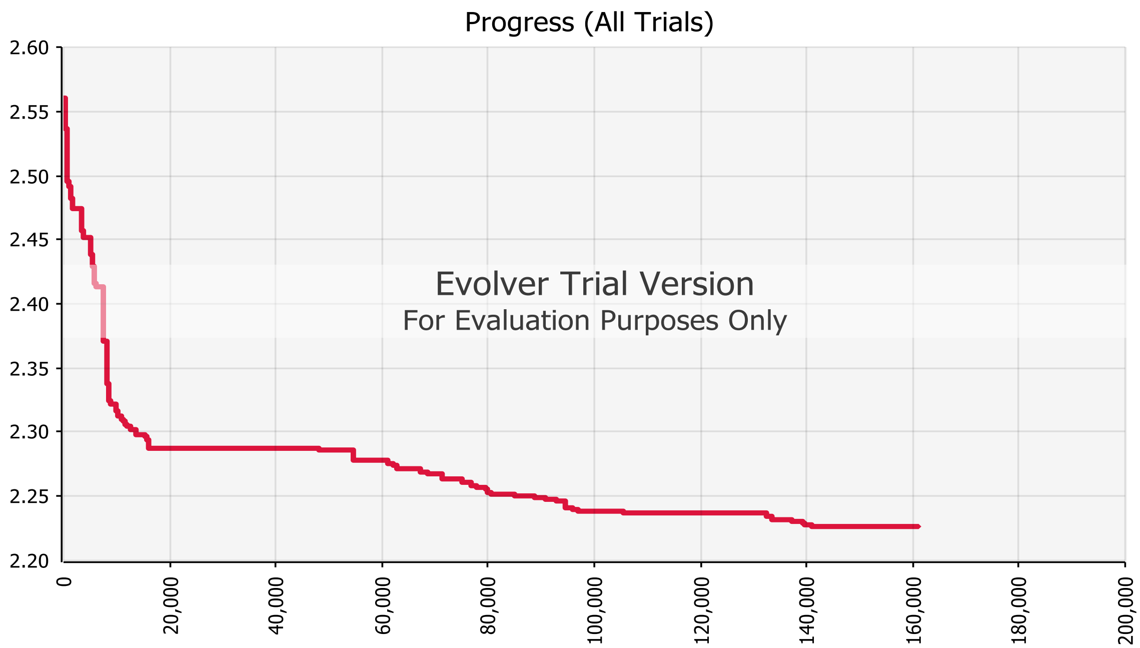
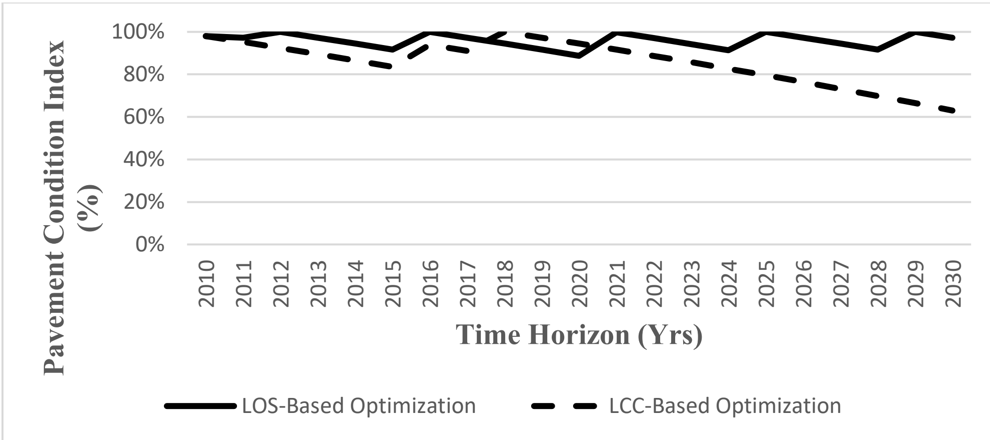
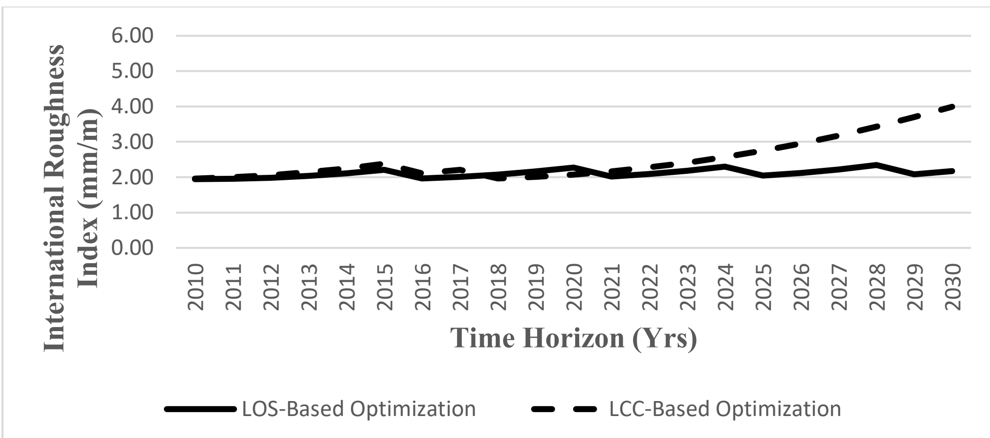


Figure 5.9: Evolver^{TM} first scenario optimization summary

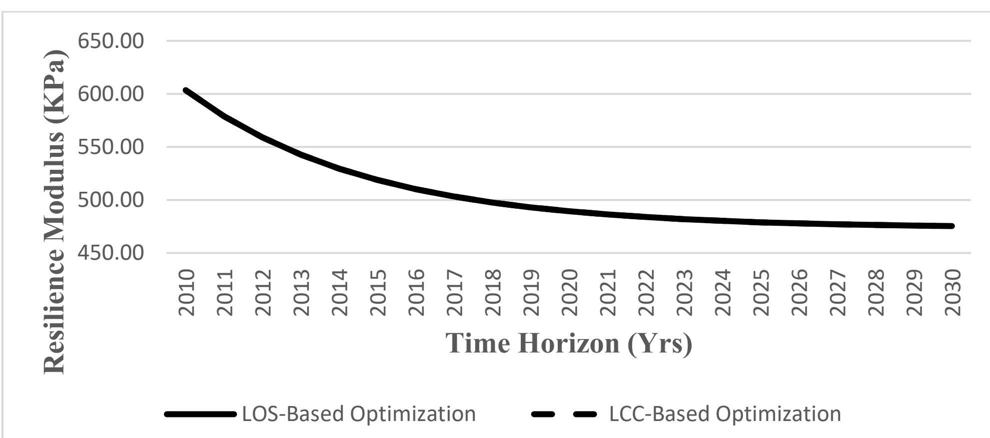
To demonstrate model analysis and results, corridors 18 and 20 conditions and level of service for both analysis scenarios, LOS-based and LLC-based optimization, are shown in Figures 5.10 and 5.11. The LOS-based scenario involves earlier intervention actions and an additional number of M&R actions to comply with the optimization objective function and constraints. For corridor 18, it can be noted that there is no change in its structural condition where no major rehabilitation or reconstruction took place during both optimization scenarios. On the other hand, it is different for corridor 20. Corridor 20 is located in the flooding zone and was affected by the 2017 flood in that area. A noticeable decrease in condition and LOS occurred that year, followed by immediate intervention in the following year in the LOS-based scenario and a delayed intervention in the LCC-based scenario. Although the LCC-based scenario offers a considerable reduction in M&R interventions number and costs, the end-users will encounter reduced conditions and LOS by the end of the planning horizon. This will hinder the network users on that corridor.



(a) Pavement Condition Index

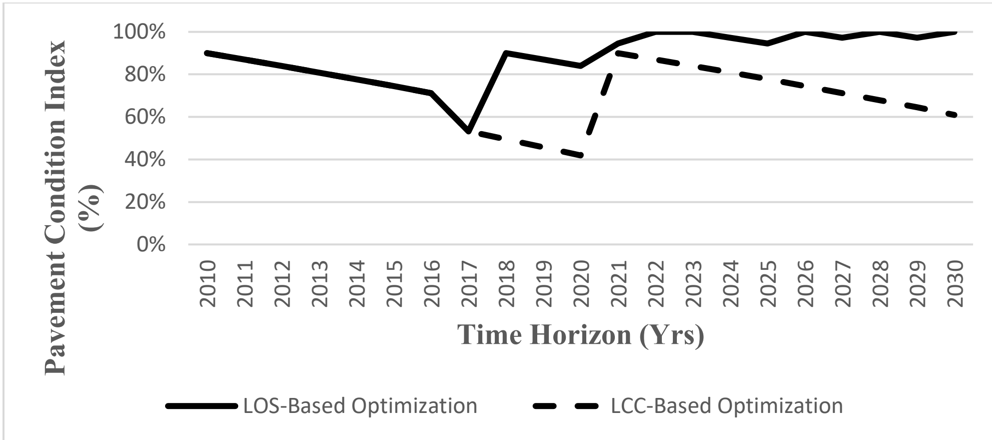


(b) Level of Service

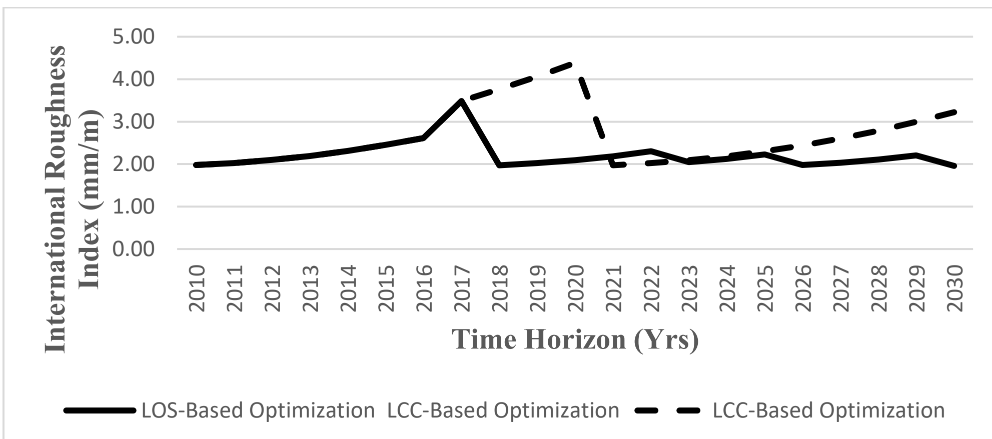


(c) Pavement Resilience Modulus

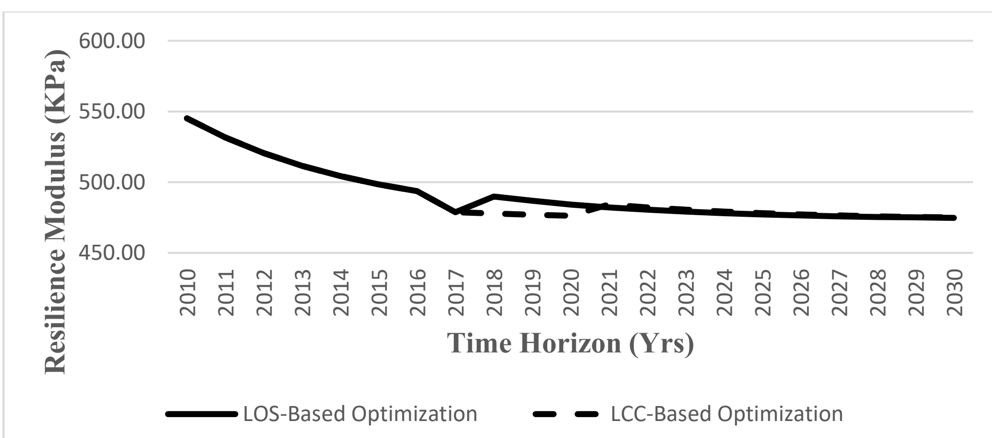
Figure 5.10: Optimized condition and level of service for corridor 18



(a) Pavement Condition Index



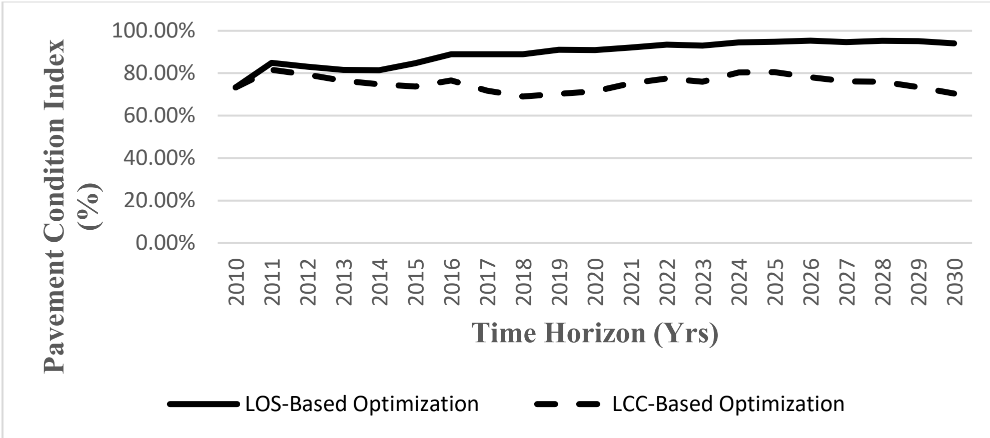
(b) Level of Service



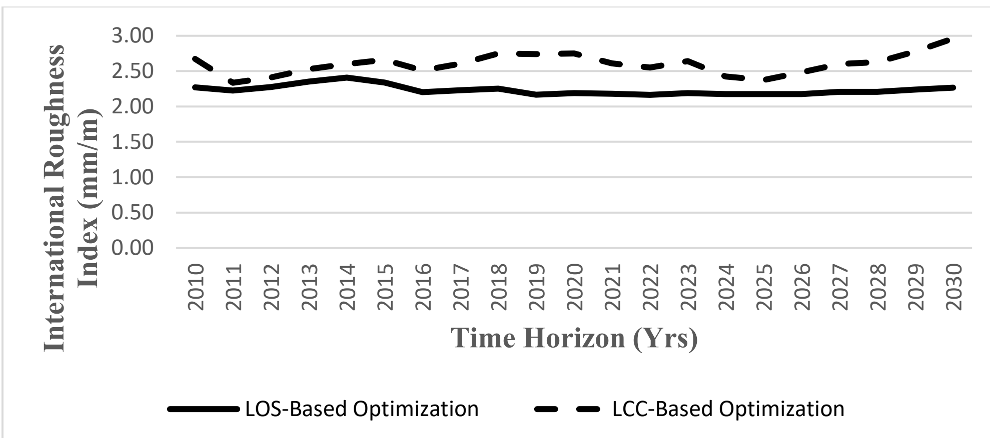
(c) Pavement Resilience Modulus

Figure 5.11: Optimized condition and level of service for corridor 20

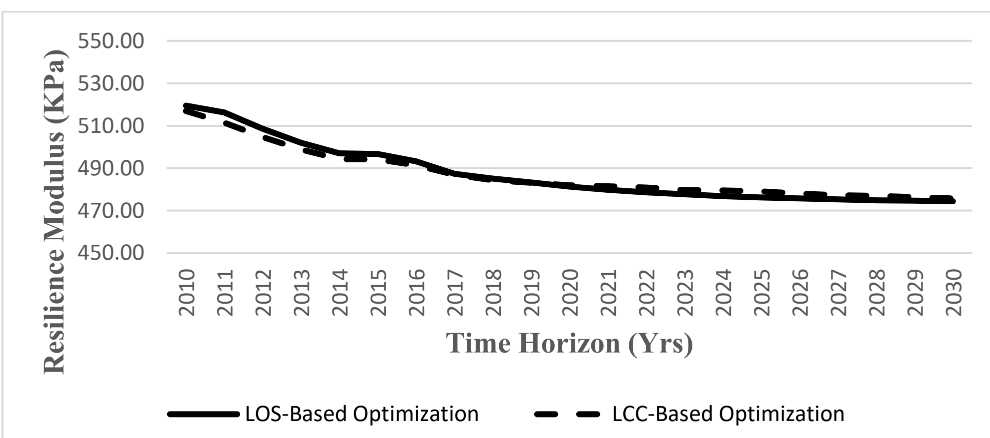
As stated earlier, the proposed model was utilized by applying two different objective functions. The LCC-based optimization scenario reflects decision-makers and municipalities' priorities and approaches to plan M&R for pavement networks. Both scenarios reflect the proposed resilience definition. The LCC-based scenarios also maintained pavement condition and LOS within the acceptable thresholds. The 2017 floods randomly hit several network corridors, yet the model mitigated any sudden and significant deterioration for both: condition and LOS. The overall weighted average surface condition, structural condition, and LOS fell within the acceptable limits reaching 75.33%, 487.24 KPa (78%), and 2.60 mm/m. Figure 5.12 demonstrates the pavement network condition and LOS throughout the planning horizon under aging, freeze-thaw cycles, flooding effect, and under the expected climatic conditions forecasted for the planning horizon.



(a) Pavement Condition Index



(b) Level of Service

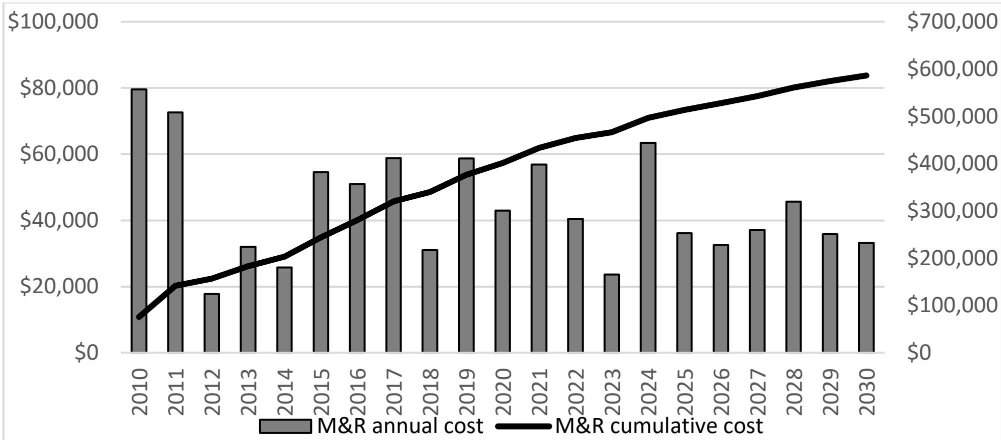


(c) Pavement Resilience Modulus

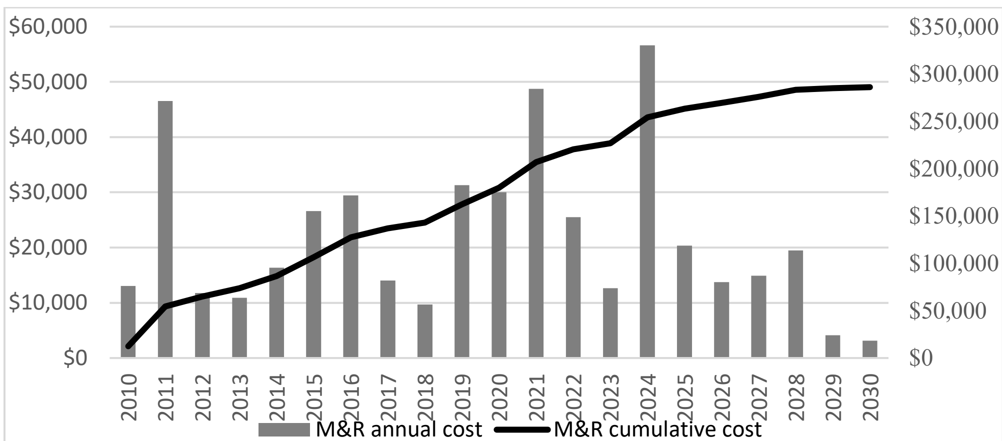
Figure 5.12: Optimized pavement network condition and LOS under annual Freeze-Thaw cycles, flooding, and aging

As shown in Figure 5.13, an NPV of $586k and $286k were allocated to carry out the M&R for the pavement network throughout the planning time horizon for both optimization scenarios while maintaining a network LOS threshold of 2.7 mm/m. Though the resulting allocated budget difference is almost $300k, the average network IRI ranged from 2.60 mm/m for the LOS-based scenario to 2.23 mm/m for the LCC-based scenario. The LCC-based scenario puts the network on the verge of turning into a fair LOS condition if any unforeseen and unexpected events occur throughout the network life cycle. Furthermore, the M&R time required to maintain the pavement network based on the results mentioned above equals 25k hrs and 10k hrs for both LOS-based and LCC-based scenarios, respectively, as demonstrated in Figure 5.13. The PCI value ranged from 89.5% to 75.3%, respectively. It is essential to notice that the average meter NPV costs to maintain the previously mentioned optimized condition values were $4.67/m and $2.28/m for both LOS-based and LCC-based scenarios, respectively. Therefore, the LCC-based scenario gives more rational end results for the model and matches municipalities' practices while planning for pavement M&R.

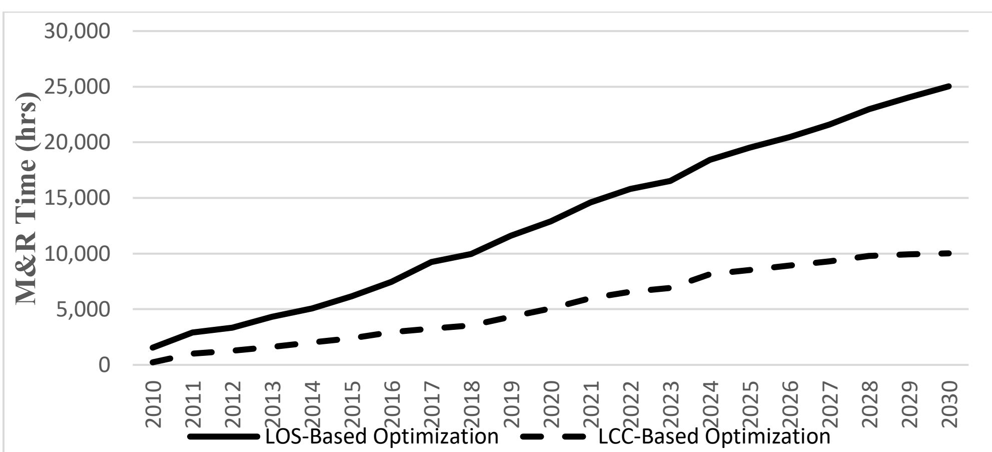
It is worth mentioning that the NPV costs/m to maintain the pavement corridors in this case study is significantly less than the NPV cost to maintain roads in the City of Montreal, which is $17.8/m. These results do not contradict each other. Whereby looking at the City of Montreal dataset in Appendices A, B, and C, the deterioration in the pavement condition throughout the eight years data age was severe, which indicates poor M&R intervention action planning and an insignificant M&R investment in the pavement network under study. This also serves as a validation of the present model.



(a) Recovery cost - LOS-based scenario



(b) Recovery cost - LCC-based scenario



(c) Recovery time

Figure 5.13: Network annual and cumulative recovery cost and time

The resulting optimized M&R plan timetable of the proposed model for the more efficient and budget-friendly scenario is demonstrated in Table 5.7 and Figure 5.14. Major intervention actions took place early in the network life cycle to offset the poor conditions and LOS existing in the pavement network at the start of the analysis. The model condition and LOS constraints also pushed the model in that direction to keep the overall pavement condition and LOS within acceptable limits later throughout the planning horizon, thus imposing early major intervention actions to maintain network resiliency based on the proposed resilience definition. Appendix D demonstrates the detailed optimized M&R intervention plan based on the LCC optimization scenario. Number 1 demonstrates Minor rehabilitation activity, number 2 demonstrates major rehabilitation activity, and number 3 demonstrates reconstruction in each corridor/year cell in Appendix D.

Table 5.7: Optimized M&R intervention plan timetable

Year	**Minor Rehabilitation**	**Major Rehabilitation**	**Reconstruction**	**Total**
2010	0	2	0	**2**
2011	3	8	0	**11**
2012	0	1	0	**1**
2013	1	0	0	**1**
2014	1	1	0	**2**
2015	2	0	1	**3**
2016	4	4	0	**8**
2017	2	3	0	**5**
2018	2	0	0	**2**
2019	4	3	0	**7**
2020	4	3	0	**7**
2021	3	5	0	**8**
2022	3	4	0	**7**
2023	1	1	0	**2**
2024	6	5	0	**11**
2025	0	3	0	**3**
2026	2	0	0	**2**
2027	1	1	0	**2**
2028	4	2	0	**6**
2029	2	0	0	**2**
2030	1	0	0	**1**
Total	**46**	**46**	**1**	**93**

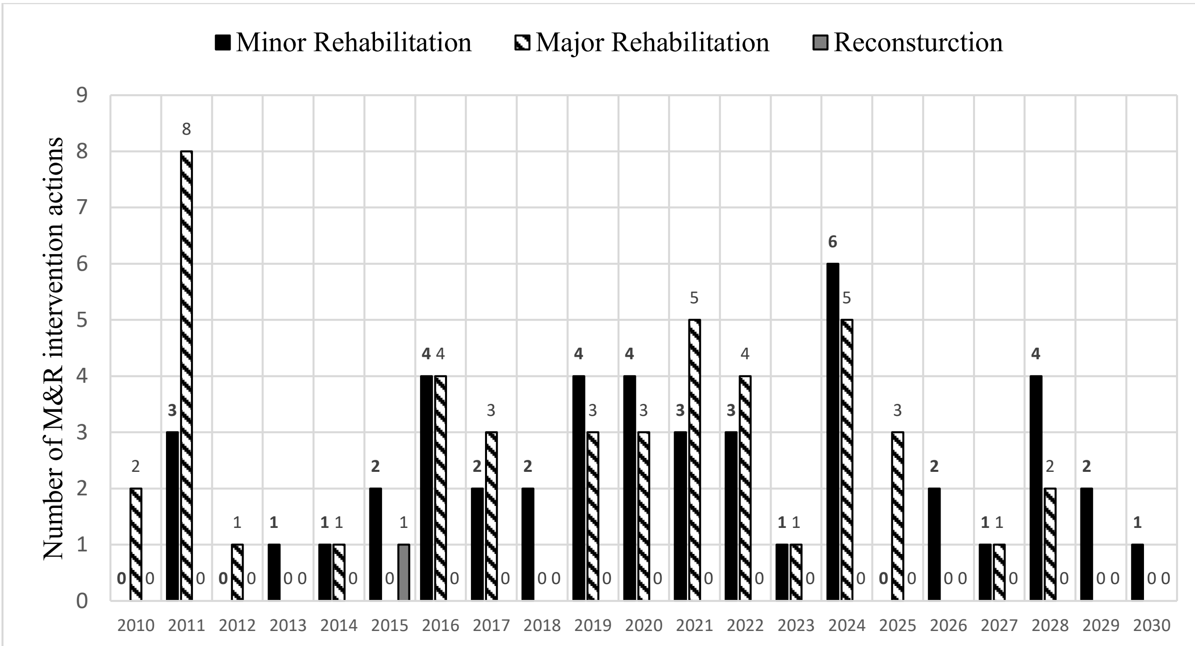


Figure 5.14: Optimized M&R intervention plan layout

5.5. Sensitivity Analysis

Sensitivity analysis demonstrates the influence of inputs variables uncertainties by analyzing the output variables' results. The brute-force method was utilized to assess model sensitivity with respect to the minimum required LOS for the pavement network. The brute-force method involves recomputing the model with different input values to compute the changes in model outputs. In this case, the LOS threshold was increased and decreased by 10% and 20% creating four new model scenarios to be computed and achieve a new M&R plan with different output values, as shown in Table 5.8. The LCC-base model was chosen to perform sensitivity analysis, which aligns with decision-makers' perspective regarding the M&R for municipal infrastructures. Sensitivity analysis also brings more in-depth knowledge of model inputs and outputs and assists them with system improvement decisions and investment worth.

Table 5.8: Sensitivity analysis scenarios

	-20% LOS	*-10% LOS*	*Original*	*+10% LOS*	*+20% LOS*
Minimum average network IRI (mm/m)	3.24	2.97	2.70	2.43	2.16

The LCC-based model was recomputed for the newly formed models based on the new LOS constraint. The associated PCI, IRI, M&R cost and time, and the total number of interventions were calculated and recorded for each scenario. The percentage change or variation of each of the previously mentioned outputs from the original LCC-based scenario was then recomputed as shown in Table 5.9. Figure 5.15 also demonstrates that change in the form of a tornado chart. It is observed that enhancing LOS by reducing IRI constraints would result in a minor pavement network condition and LOS enhancement but would be accompanied by a significant increase in M&R cost and time. Each 1% enhancement in pavement IRI will increase the associated M&R costs and time by 4% and 6%, respectively.

On the other hand, accepting lower LOS threshold limits would slightly decrease pavement network conditions and LOS. The savings in M&R cost for that loss of pavement network condition and LOS is with a ratio of 2:1 relative to the loss of pavement LOS. Every 1% increase in pavement IRI value will be accompanied by an approximate percentage decrease in M&R cost and time of 2% each.

Table 5.9: Sensitivity analysis scenarios results for each scenario/model output

Sensitivity analysis scenario	-20% LOS	-10% LOS	Original	+10% LOS	+20% LOS
Minimum average network IRI (mm/m)	3.24	2.97	2.7	2.43	2.16
Model outputs	*%Change of each output value from the original scenario*				
Weighted average network condition	-8.10%	-3.41%	0.00%	6.73%	11.53%
Weighted average network IRI	19.50%	8.08%	0.00%	-8.85%	-19.15%
Total number of interventions	-32.20%	-15.05%	0.00%	67.74%	123.25%
Network M&R cost	-39.36%	-16.97%	0.00%	37.75%	78.30%
Network M&R time	-45.25%	-21.45%	0.00%	62.78%	128.32%

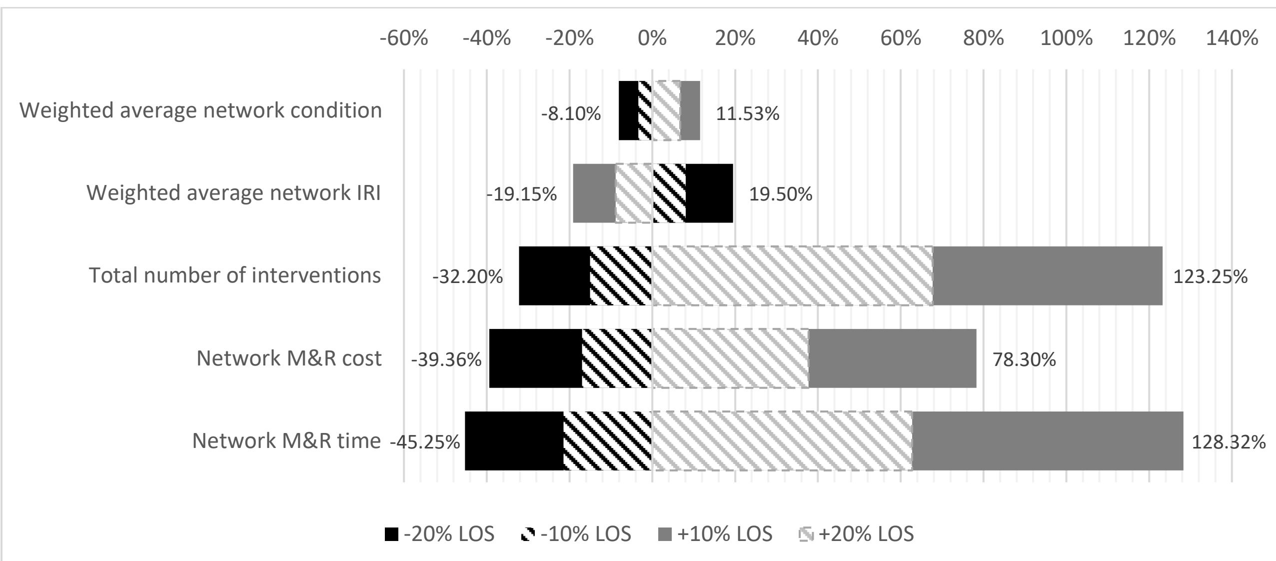


Figure 5.15: Tornado chart for sensitivity analysis results for different model outputs

Figure 5.16 presents each network parameter output slope for the required LOS threshold change. As mentioned, the resulting sensitivity analysis conclusion matches the initially utilized IRI threshold. The utilized IRI threshold works as a near-ideal spot to achieve satisfactory network LOS with an affordable budget.

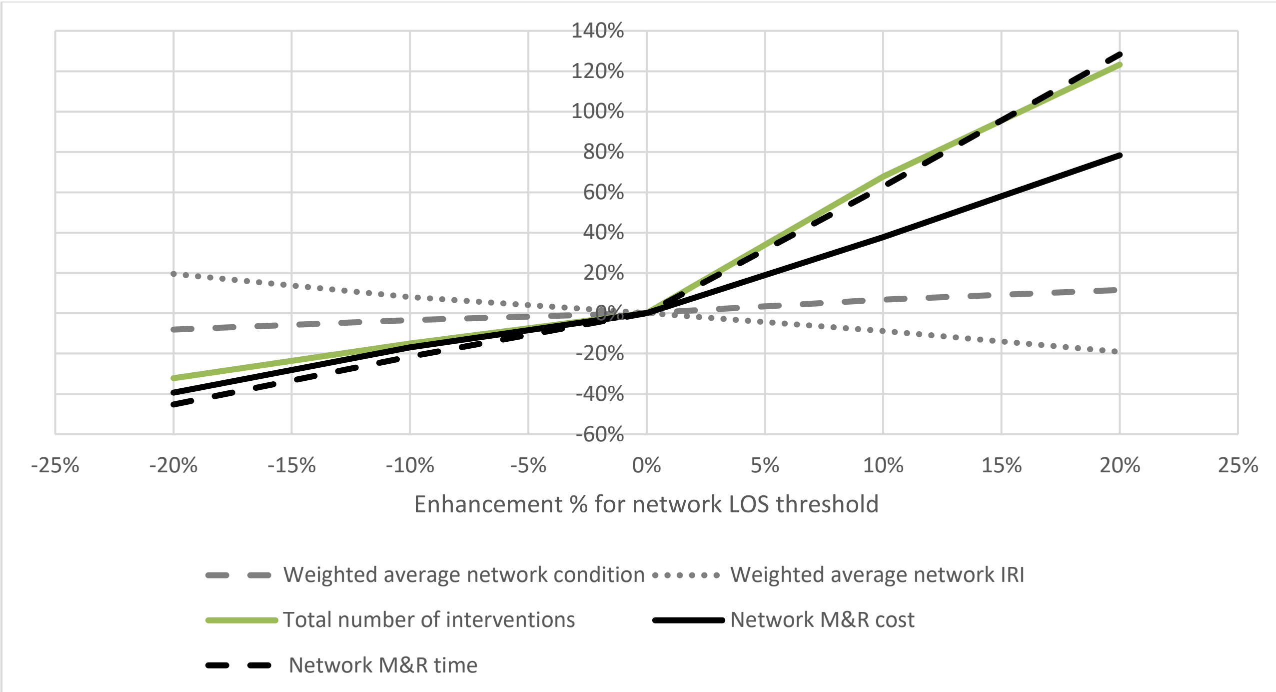


Figure 5.16: Sensitivity of model outputs based on LOS constraint

5.6. Summary

The updated model application on the selected case study demonstrates proof of concept and establishes model testing. Resilience indicators models were updated to include the two types of pavement condition, surface and structural. In addition, climatic data and flooding were included while building the primary model. Finally, two core optimization model scenarios were applied to a selected portion of the pavement network of Pierrefonds-Roxboro. The optimization demonstrated that; although the LCC scenario put LOS in a near-fair condition, significant savings in the allocated budget are gained compared to the LOS scenario, with nearly 50% savings. Hence, the LCC scenario offers a budget-friendly approach while incorporating the resiliency concept in pavement M&R planning.

Sensitivity analysis of the LOS constraints showed that stricter LOS constraints would significantly improve pavement condition and LOS. Nevertheless, this would be accompanied by a significant increase in the allocated budget. The decreased accompanied budgetary cost is noticeable with less strict LOS constraints. With a tight budget this would notably aid the City decision-makers while planning for pavement M&R. This chapter also demonstrates the challenges encountered while trying to achieve the full potential of the proposed model.

It should be noted that while the proposed method allows for probabilistic analysis by incorporating the uncertainties related to different parameters, the present study utilized only the mean values. Thus, the current analysis is deterministic and provides an assessment of the pavement resiliency for fixed values of the parameters.

CHAPTER 6 – CONCLUSIONS

6.1. Summary

This research integrates resilience into the asset management concept. Through the review of the previous literature, quite a few findings were found, such as but not limited to, (1) several conceptual definitions were investigated from the disaster management concept and had not introduced a system's aptitude to maintain a resilient condition during its life-cycle under the different type of events and conditions while cost and time limitations exist, (2) most of the studies dealt with resilience as a consequence of a disaster while it is a continuous process (Mostafavi et al. 2017), (3) most of resilience assessment models need an intensive database to be available for usage, which is not the case for most of the countries. Accordingly, other models should be used to mitigate the absence of such a database and reliable historical data, (4) the effect of previous non-extreme disruption events on resilience was not considered thoroughly, though it was mentioned thoroughly as a part of the literature, and (5) even though, there exist multiple optimization models for selecting near-optimal M&R intervention plans for pavement networks, resilience-based decision making has not been thoroughly studied.

Accordingly, the previous literature comprehensively examined the resilience definition to bypass the abovementioned limitations. A definition of resilience was proposed that integrates asset management and resilience concepts. The proposed definition captures the different resilience indicators and generates a practical objective targeting a satisfactory LOS while attaining the maximum M&R plan gains within an appropriate budget allocation. The investigation of previous literature continues after that to identify resilience indicators. Each indicator was generally demonstrated in specific for pavement networks. Therefore, resilience indicators were categorized into three categories that reflect system resiliency and the proposed definition of resilience. Those categories are (1) asset-based indicators, (2) disruption-based indicators, and (3) recovery-based indicators. A sub-category of each category was devised to give a comprehensive insight and reflection of each indicator on infrastructure resiliency.

After identifying and formulating resilience indicators, a resilience-based asset management model was developed. The author's resilience definition was deciphered into an optimization model. The model was utilized through an advanced MS Excel™ environment Evolver™ Version 8.1. The model was initially applied to a pilot case study to emphasize model creation's main objective and work as a baseline for model inputs development. Models input such as pavement structural condition, extreme events effect, climatic conditions, etc., were included and added based on that, as shown in the main case study through Chapter 5. The models used to reflect extreme and non-extreme events' effects were deterministic, mainly due to the need to verify the model and match it with the actual case study scenario. Also, the model was utilized to create two main scenarios reflecting the proposed asset management-based resilience definition: the LOS-based and LCC-based scenarios. The latter scenario provides a more realistic conclusion that coincides with municipalities' priorities when planning pavement network M&R. This was demonstrated when the optimization's objective function was changed from minimizing IRI to minimizing LCC. Accordingly, the LCC-based scenario model responded with a 40% save on M&R costs and a decrease of 20% of LOS compared to the LOS-based scenario.

The final step was to derive a Resilience Index based on the modeled scenario and the associated resilience indicators used as an input for the model. PCA was applied to obtain the weights for each indicator and compute RS. Each indicator weight calculated through PCA is unique for each case study, where it is a data-driven approach that mitigates the ambiguity of the resulting weights. IBM SPSS® was utilized to perform PCA analysis. In the pilot case study, only the first and second components had an eigenvalue greater than one, promoting the use of both components to summarize the dataset and obtain the required RS. The dataset, in this case, was the LCC-based scenario optimization output. It was concluded that integrating resiliency and asset management concepts when planning an infrastructure M&R would significantly affect budget allocation in the infrastructure network and mitigate the sudden loss of LOS through its lifecycle. The model is applicable to other types of infrastructure as long resilience indicators can be defined with respect to the infrastructure type. In case of a lack of data, which is common in most developing countries, the model will still be applicable if any missing data can be reasonably assumed.

6.2. Contributions

The proposed research methodology provided a supple-inclusive tool to obtain an optimized M&R plan for municipal infrastructure networks while integrating resilience and asset management concepts. Thru review of the current literature practices, model development, and implementation, the significant contributions of this research were disclosed and could be summarized as follows:

- Formulate a conclusive infrastructure resilience definition that integrates resilience and asset management concepts. This definition fits the QUÉBEC Infrastructure Plan 2021/2031, which emphasizes the importance of maintaining a superior LOS while implementing proper budget allocation.
- Identify and classify key resilience indicators such that to reflect and incorporate resiliency into asset management.
- Develop a resilience-based asset management methodology for pavement networks. This provides a systematic approach to implementing proper recovery strategies for

regular and extreme events into the M&R intervention plan while considering the common deterioration, climatic conditions, and aging effects.

- An optimization model was developed (and implemented in MS Excel^{TM} environment utilizing EvolverTM Version 8.1) that provides an efficient tool to study the different optimization objective scenarios based on the conclusive resilience definition while adhering to decision-makers' target. Furthermore, the model is capable of capturing. Therefore, this implies that the RS value for each corridor will be dynamic depending on which years it is calculated.
- The developed resilience-based asset management framework is distinctive where it combines notions from both performance-based and risk-based asset management approaches. Performance measures are reflected through LOS and condition constraints, while the risk is reflected via both extreme and non-extreme events applications.
- Design a PCA-based methodology to acquire each resilience indicator weight based on the available network data. The methodology involves deriving an extension for PCA analysis to generate the weights of each resilience indicator by analyzing the resulting principal components' outputs.

6.3. Limitations

The main limitations of this research are summarized as follows:

- The evaluation of the pavement structural condition and its interaction with the various disruptive events was not widely covered due to the lack of case study data for the subject matter.
- Flooding hazard scenario implementation was put into effect in a definitive year.

- M&R intervention plan only dealt with repair and rehabilitation procedures and retrofit was not included.
- Redundancy is a dynamic resilience feature, especially for road networks, yet it was dealt with as a static feature throughout the planning horizon. Nevertheless, this did not affect the redundancy analysis, where no significant change in links and nodes occurred through the pavement network lifecycle.
- The developed optimization model was tested and validated by comparing model results and pilot and main case studies' actual data. Nevertheless, further validation is required to capture model performance for other case studies.

6.4. Opportunities for Future Work

Based on the research methodology and implementation throughout, the following are some recommendations for future work:

- Investigate the existing asset and disaster management policies and how they can be integrated with their M&R intervention plans to enhance the established methodology.
- Incorporate further resilience indicators and evaluate their significance to expand model usage on other types of infrastructures.
- Expand the regular and disruption event scenarios, such as snowstorms, snow removal, etc., and include their effect on the pavement network condition.
- Expand M&R intervention actions to include retrofitting.
- Examine the effect of interdependency along with the integrated M&R plans between the different municipal infrastructures to establish a comprehensive resilience-based framework to manage interdependent infrastructures.

- Consider utilization simulation for flooding modeling within the optimization model for an improved M&R plan and to address flooding occurrence uncertainties. The use of Hazus is another mean to address flooding's adverse effects.

REFERENCES

AASHTO, and Transportation Officials Joint Task Force on Pavements. (2001). "Pavement management guide.".

Abaza, K., and Ashur, S. (1999). "Optimum decision policy for management of pavement maintenance and rehabilitation." *Transportation Research Record: Journal of the Transportation Research Board,* (1655), 8-15.

Abeyasekera, S. (2005). "Chapter XVIII Multivariate methods for index construction." *Reading (UK): University of Reading. hlm,* 377-378.

Abu-Samra, S. (2014). "Integrated asset management system for performance-based road maintenance contracts." Master Dissertation, American University in Cairo, Cairo, Egypt.

Adedimila, A., Olutaiwo, A., and Kehinde, O. (2009). "Models for a Developing Country." *J.Eng.Applied Sci,* 4(1), 13-26.

Agarwal, J. (2015). "Improving resilience through vulnerability assessment and management." *Civ.Eng.Environ.Syst.,* 32(1-2), 5-17.

Ahmed, F., Thompson, J., Kim, D., Huynh, N., and Carroll, E. (2021). "Evaluation of pavement service life using AASHTO 1972 and mechanistic-empirical pavement design guides." *International Journal of Transportation Science and Technology*.

Alaloul, W. S., Altaf, M., Musarat, M. A., Faisal Javed, M., and Mosavi, A. (2021). "Systematic review of life cycle assessment and life cycle cost analysis for pavement and a case study." *Sustainability*, *13*(8), 4377.

Alderson, D. L., Brown, G. G., and Carlyle, W. M. (2015). "Operational models of infrastructure resilience." *Risk Analysis,* 35(4), 562-586.

Alyami, Z. (2012). "*A Two-Phase Maintenance and Rehabilitation Framework for Pavement Assets Under Performance Based Contracts."* (Master's thesis, University of Waterloo).

Amin, M. S. R., and Amador-Jiménez, L. E. (2015). “Travel demand modeling to simulate traffic loads for pavement deterioration curves: dealing with aggregate data at urban and regional scales.” *Canadian Journal of Civil Engineering*, *42*(12), 1049-1062.

ASCE (American Society of Civil Engineers). (2017). "*ASCE Infrastructure Report Card.*" American Society of Civil Engineering. ⟨https://www.infrastructurereportcard.org/⟩ (May 24, 2017).

Attoh-Okine, N. O., Cooper, A. T., and Mensah, S. A. (2009). "Formulation of resilience index of urban infrastructure using belief functions." *IEEE Systems Journal,* 3(2), 147-153.

Baroud, H., Barker, K., Ramirez-Marquez, J. E., and Rocco, C. M. (2015). "Inherent costs and interdependent impacts of infrastructure network resilience." *Risk Analysis,* 35(4), 642-662.

Bakhtiari, M. S., and Officer, O. (2020). *ACATS Project Final Report*. Technical report, Canadian Urban Transit Research and Innovation Consortium.

Babashamsi, P., Khahro, S. H., Omar, H. A., Al-Sabaeei, A. M., Memon, A. M., Milad, A., ... and Yusoff, N. I. M. (2022). “Perspective of Life-Cycle Cost Analysis and Risk Assessment for Airport Pavement in Delaying Preventive Maintenance.” *Sustainability*, *14*(5), 2905.

Bocchini, P., Frangopol, D. M., Ummenhofer, T., and Zinke, T. (2013). "Resilience and sustainability of civil infrastructure: Toward a unified approach." *J Infrastruct Syst,* 20(2), 04014004.

Bro, R., and Smilde, A. K. (2014). "Principal component analysis." *Analytical Methods,* 6(9), 2812-2831.

Brownjohn, J., and Aktan, E. (2013). "Improving resilience of infrastructure: the case of bridges." *Structures Congress 2013: Bridging Your Passion with Your Profession,* ASCE, 1812-1821.

Chan, J., and Teknomo, K. (2016). “Road reconstruction and redundancy analysis on the road network: A case study of the Ateneo de Manila University network.” *Procedia-Social and Behavioral Sciences*, *218*, 56-75.

Chetverikov, A. O. (2021). “Scientific Facilities as a Subject Matter of Infrastructure Law”: Une Approche Québécoise. *Kutafin Law Review*, *8*(3), 485-494.

Chang, S. E., McDaniels, T., Fox, J., Dhariwal, R., and Longstaff, H. (2014). "Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments." *Risk Analysis,* 34(3), 416-434.

Chootinan, P., Chen, A., Horrocks, M. R., and Bolling, D. (2006). "A multi-year pavement maintenance program using a stochastic simulation-based genetic algorithm approach." *Transportation Research Part A: Policy and Practice,* 40(9), 725-743.

City of Toronto. (2013). City of Toronto Road Classification System: Summary Document.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010). "Framework for analytical quantification of disaster resilience." *Eng.Struct.,* 32(11), 3639-3649.

Cimellaro, G. P., Villa, O., and Bruneau, M. (2014). "Resilience-based design of natural gas distribution networks." *J Infrastruct Syst,* 21(1), 05014005.

Creese, S., Goldsmith, M. H., and Adetoye, A. O. (2011). "A logical high-level framework for critical infrastructure resilience and risk assessment." *Cyberspace Safety and Security (CSS), 2011 Third International Workshop on,* IEEE, 7-14.

Corson, C. (2010). “Shifting environmental governance in a neoliberal world: US AID for conservation.” *Antipode*, *42*(3), 576-602.

Cuppens, A., Smets, I., and Wyseure, G. (2012). "Definition of realistic disturbances as a crucial step during the assessment of resilience of natural wastewater treatment systems." *Water Science and Technology,* 65(8), 1506-1513.

Doré, G., Drouin, P., Pierre, P., and Desrochers, P. (2005). « Estimation of the relationships of road deterioration to traffic and weather in Canada.” *Transport Canada, Final Report*.

Ding, C., and He, X. (2004). "K-means clustering via principal component analysis." *Proceedings of the twenty-first international conference on Machine learning,* ACM, 29.

El-Assaly, A., Ariaratnam, S. T., and Hempsey, L. (2002). "Development of deterioration models for the primary highway network in Alberta, Canada." *Canadian Society for Civil Engineering-30th Annual Conference: 2002 Challenges Ahead.*

El-Badawy, S. M., Bayomy, F. M., Santi, M., and Clawson, C. W. (2011). “Comparison of Idaho pavement design procedure with AASHTO 1993 and MEPDG methods.” In *Transportation and Development Institute Congress 2011: Integrated Transportation and Development for a Better Tomorrow* (pp. 586-595).

El Rashidy, R. A. H. (2014). “The resilience of road transport networks redundancy, vulnerability and mobility characteristics.” (Doctoral dissertation, University of Leeds).

FCM (Federation of Canadian Municipalities). (2016). "*The Canadian Infrastructure Report Card*." ⟨http://www.canada infrastructure.ca/en/⟩ (May 12, 2016).

Ferreira, A., Picado-Santos, L. d., Wu, Z., and Flintsch, G. (2011). "Selection of pavement performance models for use in the Portuguese PMS." *International Journal of Pavement Engineering,* 12(1), 87-97.

FHWA. (2002b). “Highway Economic Requirements Systems - State Version Technical Report.” U.S.: FHWA-IF-02-060.

Francis, R., and Bekera, B. (2014a). "A metric and frameworks for resilience analysis of engineered and infrastructure systems." *Reliab.Eng.Syst.Saf.,* 121 90-103.

Fwa, T., Chan, W., and Tan, C. (1996). "Genetic-algorithm programming of road maintenance and rehabilitation." *J.Transp.Eng.,* 122(3), 246-253.

Gao, B. (2004). *A GIS-Enabled Multi-Year Pavement Rehabilitation Needs Analysis System.* Georgia Institute of Technology.

Gay, L. F., and Sinha, S. K. (2012). "Novel resilience assessment methodology for water distribution systems." *Pipelines 2012@ Innovations in Design, Construction, Operations, and Maintenance, Doing More with Less,* ASCE, 61-69.

Giglio, J. M., Friar, J. H., and Crittenden, W. F. (2018). “Integrating lifecycle asset management in the public sector.” *Business Horizons*, *61*(4), 511-519.

Haas, R., Hudson, W. R., and Zaniewski, J. P. (1994). *Modern pavement management.*

Haas, R., Tighe, S., Yeaman, J., and Falls, L. C. (2008, September). "Long term warranty provisions for sustained preservation of pavement networks. "In *Proc., Transp. Assoc. of Canada Annual Conf., Toronto*.

Haas, R., Felio, G., Lounis, Z., and Falls, L. C. (2009, October). "Measurable performance indicators for roads: Canadian and international practice." In *Proceedings of the 2009 Annual Conference of the Transportation Association of Canada, Vancouver, British Columbia*.

Haider, S. W., Chatti, K., and Baladi, G. Y. (2012). "Long-Term Pavement Performance Effectiveness of Preventive Maintenance Treatments Using Markov Chain Algorithm." *Eng.J.,* 16(4), 149-158.

Hajj, E. Y., Loria, L., and Sebaaly, P. E. (2010). "Performance evaluation of asphalt pavement preservation activities." *Transportation research record*, *2150*(1), 36-46.

Herrera, E. K., Flannery, A., and Krimmer, M. (2017). "Risk and resilience analysis for highway assets." *Transp.Res.Rec.,* 2604(1), 1-8.

Highway Preservation System. (January 2010). "Pavement Condition Evaluation Manual." Hamilton: Highway Preservation Systems.

Holt, A., Sullivan, S., and Hein, D. K. (2011, September). "Life cycle cost analysis of municipal pavements in Southern and Eastern Ontario." *In Transportation successes: let's build on them. Congress et Exhibition de l'Association des Transports du Canada. Les Success en Transports: Une Tremplin vers l'Avenir*.

Horak, E., Hefer, A., Emery, S., and Maina, J. (2015). "Flexible road pavement structural condition benchmark methodology incorporating structural condition indices derived from Falling Weight Deflectometer deflection bowls." *Journal of Civil engineering and Construction*, *4*(1), 1-14.

Ikpong, A., and Bagchi, A. (2014). "New method for climate change resilience rating of highway bridges." *J.Cold Regions Eng.,* 29(3), 04014013.

InfraGuide. (2003). "Planning and Defining Municipal Infrastructure Needs." Federation of Canadian Municipalities and National Research Council, Ottawa, Ontario, Canada.

Ip, W., and Wang, D. (2009). "Resilience evaluation approach of transportation networks." *Computational Sciences and Optimization, 2009. CSO 2009. International Joint Conference on,* IEEE, 618-622.

Jacobi, R. (2012). "*Le rapport des villes à leur fleuve: le cas de Québec et du Saint-Laurent*. " (Doctoral dissertation, Université de Neuchâtel).

Jenelius, E. (2010). Redundancy importance: Links as rerouting alternatives during road network disruptions. *Procedia Engineering*, *3*, 129-137.

Jorn, R. K. (2005). "Use of Asset Values in Pavement Management Systems." *Kokbjerg 5*.

Jung, D., Kang, D., Liu, J., and Lansey, K. (2013). "Improving resilience of water distribution system through burst detection." *Proceedings 2013 ASCE Environment and Water Resources Institue Annual Conference*.

Karunaratne, K. C., and Burn, C. R. (2003, July). "Freezing n-factors in discontinuous permafrost terrain, Takhini River, Yukon Territory, Canada." In *Proceedings of the 8th International Conference on Permafrost* (Vol. 1, pp. 519-524).

Khan, A. J., Huq, F., & Hossain, S. Z. (2014). "Application of jute geotextiles for rural road pavement construction." *In Ground Improvement and Geosynthetics* (pp. 370-379).

Knudson, M., and District, PE Tualatin Valley Water. (2013). "The Oregon Resilience Plan For Water and Wastewater Systems." *Pipelines 2014: From Underground to the Forefront of Innovation and Sustainability,* ASCE, 2211-2220.

Krishnan, V. (2010). "Constructing an area-based socioeconomic index: A principal components analysis approach." *Edmonton, Alberta: Early Child Development Mapping Project*.

Lam, C., and Tai, K. (2012). "Evaluating the reliability of infrastructure networks by resilience analysis." *2012 IEEE International Conference on Industrial Engineering and Engineering Management,* IEEE, 1165-1169.

Leiva-Villacorta, F., Vargas-Nordcbeck, A., and Aguiar-Moya, J. P. (2017). “Permanent deformation and deflection relationship from pavement condition assessment.” *International Journal of Pavement Research and Technology*, *10*(4), 352-359.

Li, N. (1997). "*Development of a probabilistic based, integrated pavement management system*." (Doctoral dissertation, University of Waterloo).

Li, Z. (2005). “*A Probabilistic and Adaptive Approach to Modeling Performance of Pavement Infrastructure*.” (Doctoral dissertation, University of Texas, Texas).

Liu, F., and Wang, K. C. (1996). “Pavement performance-oriented network optimization system.” *Transportation Research Record*, 1524(1), 86–93.

Liu, Y., and McNeil, S. (2020). “Using resilience in risk-based asset management plans.” *Transportation Research Record*, *2674*(4), 178-192.

Lu, D., Tighe, S. L., and Xie, W. (2017). “Pavement Fragility Modeling Framework and Build-in Resilience Strategies for Flood Hazard.” *Transportation Research Board 96th Annual Meeting*, Washington DC, United States, No. 17-01735. 2017.

Lu, D., Tighe, S. L., and Xie, W. C. (2020). “Impact of flood hazards on pavement performance.” *International Journal of Pavement Engineering*, *21*(6), 746-752.

Lu, L., Guo, X., and Zhao, J. (2017). “A unified nonlocal strain gradient model for nanobeams and the importance of higher order terms.” *International Journal of Engineering Science*, *119*, 265-277.

Lundberg, J., and Johansson, B. J. (2015). "Systemic resilience model." *Reliab.Eng.Syst.Saf.,* 141 22-32.

Izaddoost, A., Naderpajouh, N., and Heravi, G. (2021). “Integrating resilience into asset management of infrastructure systems with a focus on building facilities.” *Journal of Building Engineering*, *44*, 103304.

Ma, B., Si, W., Zhu, D., and Wang, H. (2014). "Applying method of moments to model the reliability of deteriorating performance to asphalt pavement under freeze-thaw cycles in cold regions." *J.Mater.Civ.Eng.,* 27(1), 04014103.

Maadani, O., Shafiee, M., and Egorov, I. (2021). “Climate Change Challenges for Flexible Pavement in Canada: An Overview.” *Journal of Cold Regions Engineering*, *35*(4), 03121002.

MacKenzie, C. A., and Barker, K. (2012). "Empirical data and regression analysis for estimation of infrastructure resilience with application to electric power outages." *J Infrastruct Syst,* 19(1), 25-35.

Mahoney, J. (1990). "Introduction to prediction models and performance curves." *Course Text.FHWA Advance Course on Pavement Management,* .

McDaniels, T., Chang, S., Cole, D., Mikawoz, J., and Longstaff, H. (2008). "Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation." *Global Environ.Change,* 18(2), 310-318.

Mohamad, I. B., and Usman, D. (2013). "Standardization and its effects on K-means clustering algorithm." *Research Journal of Applied Sciences, Engineering and Technology,* 6(17), 3299-3303.

Mohammadi, A., Amador-Jimenez, L., and Elsaid, F. (2019). “Simplified pavement performance modeling with only two-time series observations: a case study of Montreal Island.” *Journal of Transportation Engineering, Part B: Pavements*, *145*(4), 05019004.

Nicolosi, V., Augeri, M., D’Apuzzo, M., Evangelisti, A., and Santilli, D. (2022). “A Probabilistic Approach to the Evaluation of Seismic Resilience in Road Asset Management.” *International Journal of Disaster Risk Science*, *13*(1), 114-124.

NSYDOT. (March 2010). “NSYDOT Network Level - Pavement Condition Assessment.” New York, U.S.: NYSDOT.

O'Rourke, T. D. (2007). "Critical infrastructure, interdependencies, and resilience." *Bridge-Washington-National Academy of Engineering-,* 37(1), 22.

Opus International Consultants (Canada) Limited. (April 2012). “Pavement Surface Condition Rating Manual.*”* Columbia: British Columbia Ministry of Transportation and Infrastructure Construction Maintenance Branch.

Organization for Economic Co-operation and Development (OECD). (1987). “Pavement Management System.” Paris, France: OECD.

Organization for economic co-operation and development - OECD. (2001). “*Performance Indicators for the Road Sector (Summary of the field tests) - Asset Management.”* Paris, France: OECD.

Ortiz-García, J. J., Costello, S. B., and Snaith, M. S. (2006). "Derivation of transition probability matrices for pavement deterioration modeling." *J.Transp.Eng.,* 132(2), 141-161.

Ouyang, M., and Dueñas-Osorio, L. (2012). "Time-dependent resilience assessment and improvement of urban infrastructure systems." *Chaos: An Interdisciplinary Journal of Nonlinear Science,* 22(3), 033122.

Ouyang, M., Dueñas-Osorio, L., and Min, X. (2012). "A three-stage resilience analysis framework for urban infrastructure systems." *Struct.Saf.,* 36 23-31.

Ouyang, M., and Wang, Z. (2015). "Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis." *Reliab.Eng.Syst.Saf.,* 141 74-82.

Panthi, K. (2009). "*A methodological framework for modeling pavement maintenance costs for projects with performance-based contracts*." (Doctoral Dissertation, Florida International University)

Park, H. M., Kim, Y. R., and Wan Park, S. (2005). “Assessment of pavement layer condition with use of multiload-level falling weight deflectometer deflections.” *Transportation research record*, *1905*(1), 107-116.

Patel, K., and Ruparathna, R. (2021). “Life cycle sustainability assessment of road infrastructure: a building information modeling-(BIM) based approach.” *International Journal of Construction Management*, 1-10.

Pedicini, S., Stolte, M., Sinha, S. K., and Smith, K. (2014). "Utility Asset Management Programming: Performance, Sustainability, and Resilience—Moving from Academia to Practice." *Pipelines 2014: From Underground to the Forefront of Innovation and Sustainability,* ASCE, 2069-2084.

Piratla, K. R., and Ariaratnam, S. T. (2013). "Performance evaluation of resilience metrics for water distribution pipeline networks." *Pipelines 2013 Conference: Pipelines and Trenchless Construction and Renewals-A Global Perspective,* .

Rababaah, H. (2005). "*Asphalt Pavement Crack Classification: A Comparative Study of Three AI Approaches: Multilayer Perceptron, Genetic Algorithms and Self-Organizing Maps*." (Doctoral dissertation, Indiana University South Bend).

Rasoulkhani, K., Mostafavi, A., Cole, J., and Sharvelle, S. (2019). "Resilience-based infrastructure planning and asset management: Study of dual and singular water distribution infrastructure performance using a simulation approach." *Sustainable Cities and Society*, *48*, 101577.

Reed, D. A., Kapur, K. C., and Christie, R. D. (2009). "Methodology for assessing the resilience of networked infrastructure." *IEEE Systems Journal,* 3(2), 174-180.

Riverside County Transportation Department. (2011). *2011 Pavement Management Report.* Riverside: County of Riverside Transportation Departement.

Saleh, M. (2016). "Simplified approach for structural capacity evaluation of flexible pavements at the network level." *International Journal of Pavement Engineering*, *17*(5), 440-448.

Saha, J. (2011). "*Evaluation of the Effects of Canadian Climatic Conditions on Pavement Performance Using the Mechanistic Empirical Pavement Design Guide."* (Master's Dissertation, University of Alberta)

Saldarriaga, J., Ochoa, S., Rodríguez, D., and Arbeláez, J. (2008). "Water distribution network skeletonization using the resilience concept." *10th Annual Water Distribution Systems Analysis Conference WDSA,* 852-864

Schnoor, H., & Horak, E. (2012). "Possible method of determining structural number for flexible pavements with the falling weight deflectometer." *SATC 2012*.

Shamsabadi, S. S., Tari, Y. S. H., Birken, R., & Wang, M. (2014, July). "Deterioration forecasting in flexible pavements due to floods and snow storms." In *EWSHM-7th European Workshop on Structural Health Monitoring*.

Shrestha, J. K. (2018). “Rural Road Network Decision Model for Hilly Regions of Nepal.” *Journal of Advanced College of Engineering and Management*, *4*, 51-64.

Shah, J., Jefferson, I., Ghataora, G., and Hunt, D. (2014). "Resilient Geotechnical Infrastructure Asset Management." *Geo-Congress 2014: Geo-characterization and Modeling for Sustainability,* 3769-3778.

Shah, S. S., and Babiceanu, R. F. (2015). "Resilience modeling and analysis of interdependent infrastructure systems." *Systems and Information Engineering Design Symposium (SIEDS), 2015,* IEEE, 154-158.

Shahnazari, H., Tutunchian, M. A., Mashayekhi, M., and Amini, A. A. (2012). "Application of soft computing for prediction of pavement condition index." *J.Transp.Eng.,* 138(12), 1495-1506.

Shekharan, A. (2000). "Pavement performance prediction by artificial neural networks." *Computational Intelligence Applications in Pavement and Geomechanical Systems,* 89-98.

Singh, P., Sinha, V. S. P., Vijhani, A., and Pahuja, N. (2018). “Vulnerability assessment of urban road network from urban flood.” *International journal of disaster risk reduction*, *28*, 237-250.

Sultana, I., Ramireddy, T., Rahman, M. M., Chen, Y., and Glushenkov, A. M. (2016). “Tin-based composite anodes for potassium-ion batteries.” *Chemical communications*, *52*(59), 9279-9282.

Statistics Canada. (2017). “*Canadian demographics at a Glance: Population growth in Canada.*” ⟨http://www.statcan.gc.ca/pub/91-003-x/2007001/4129907-eng.htm⟩ (Jan. 18, 2017).

Suman, S., and Sinha, S. (2012). "Pavement condition forecasting through artificial neural network modelling." *International Journal of Emerging Technology and Advanced Engineering,* 2(11), 474-478.

Tack, J., and J. Chou, E. (2002). "Multiyear pavement repair scheduling optimization by preconstrained genetic algorithm." *Transportation Research Record: Journal of the Transportation Research Board,* (1816), 3-8.

Timashev, S. (2011). "Resilience and preparedness of critical infrastructures." *proceedings from International Conference on Vulnerability and Risk Analysis and Management, ICVRAM 2011 and the International Symposium on Uncertainty Modeling and Analysis, ISUMA.*

Turnquist, M., and Vugrin, E. (2013). "Design for resilience in infrastructure distribution networks." *Environment Systems & Decisions,* 33(1), 104-120.

Vugrin, E. D., Warren, D. E., Ehlen, M. A., and Camphouse, R. C. (2010). "A framework for assessing the resilience of infrastructure and economic systems." *Sustainable and resilient critical infrastructure systems,* Springer, 77-116.

Vyas, S., and Kumaranayake, L. (2006). "Constructing socio-economic status indices: how to use principal components analysis." *Health Policy Plan.,* 21(6), 459-468.

Wang, F., Zhang, Z., and Machemehl, R. B. (2003). "Decision-making problem for managing pavement maintenance and rehabilitation projects." *Transportation Research Record*, 1853(1), 21-28.

Wang, N., and Zhang, W. (2016). "Network-based Assessment of Resilience of Road Systems." *Journal of Structural Safety*, Elsevier, 62, 57-65.

Westerdahl, K. S. (2014). "Societal consequences of radioactive releases in March 2011 in Japan and implications for the resilience concept." *Journal of Risk Research,* 17(9), 1147-1160.

Wood, T. J., Watson, M., Olson, R. C., LUKANEN, E. O., and Wendel, M. (2009). *Preventive Maintenance Best Management Practices of Hot Mix Asphalt Pavements.*

Xu, X., Chen, A., Jansuwan, S., Heaslip, K., and Yang, C. (2015). "Modeling transportation network redundancy." *Transportation Research Procedia,* 9 283-302.

Yang, D. Y., & Frangopol, D. M. (2019). "Life-cycle management of deteriorating civil infrastructure considering resilience to lifetime hazards: A general approach based on renewal-reward processes." *Reliability Engineering & System Safety*, *183*, 197-212.

Zhong, J. (2017).” *Rigid Pavement: Ontario Calibration of the Mechanistic-Empirical Pavement Design Guide Prediction models*.” (Master's thesis, University of Waterloo).

Zhou, H., Wan, J., and Jia, H. (2010). "Resilience to natural hazards: a geographic perspective." *Nat.Hazards,* 53(1), 21-41.

Zimmerman, K. A., Botelho, F., and Clark, D. (2000). "Taking pavement management into the next millennium." *Transportation in the New Millennium.*

Zobel, C. W. (2011). "Representing perceived tradeoffs in defining disaster resilience." *Decis.Support Syst.,* 50(2), 394-403.

Carto. (2022). (Retrieved in January 2022). https://cbcnews.carto.com/viz/de62cd96-5779-11e7-9d7c-0ef7f98ade21/public_map

Canadian Broadcasting Corporation. (2017). (Retrieved in June 2021). https://www.cbc.ca/news/canada/montreal/floodplain-map-outdated-montreal-1.4112073#:~:text=Over%20the%20past%20few%20weeks%20of%20flooding%20in,city%27s%20north%20shore%20is%20decades%20out%20of%20date.

Centre d'expertise hydrique du Québec. (2021). (Retrieved in June 2021). https://www.cehq.gouv.qc.ca/zones-inond/ZIS-20190719/index.html

Climate Atlas of Canada. (2021). (Retrieved in February 2021). https://climateatlas.ca/map/canada/fdd_2060_45#z=3&lat=61.48&lng=-82.97

Climatedata.com. (2021). (Retrieved in September 2021) https://climatedata.ca/case-study/pavement-and-extreme-temperatures-in-the-city-of-toronto/

Données Québec. (2021). (Retrieved in May 2021). https://www.donneesquebec.ca/recherche/dataset/vmtl-condition-chaussees-reseau-routier

Government of Ontario. (2021). (Retrieved in June 2021). https://www.fin.gov.on.ca/en/budget/estimates/2002-03/volume1/mnr.html

Federal Highway Association. (2022). (Retrieved in July 2022).

https://www.fhwa.dot.gov/asset/if08008/amo_05.cfm#:~:text=Generally%2C%20two%20different%20approaches%20are,evaluating%20investment%20benefits%20and%20costs

Montreal Gazette. (2017). (Retrieved in January 2022). https://montrealgazette.com/news/local-news/montreal-spends-more-on-roads-than-rest-of-canadawithworseresults#:~:text=News,Montreal%20spends%20more%20on%20roads%20than%20rest%20of%20Canada%2C%20with,what%27s%20spent%20elsewhere%20on%20roads.

National Broadcasting Company. (2017). (Retrieved in June 2021). https://www.nbcnews.com/slideshow/quebec-deep-water-historic-flooding-forces-nearly-1-900-evacuate-n757611

APPENDIX A: PIERREFONDS CASE STUDY 2010 DATA

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
1619533	de Pierrefonds boulevard	rue Prével	avenue du Chateau-Pierrefonds	381	10/26/2010	57	Mauvais	4.56	Mauvais
1619589	de Pierrefonds boulevard	rue de Nanterre	rue Grier	93	10/26/2010	54	Mauvais	4.85	Mauvais
1619608	de Pierrefonds boulevard	rue Geneviève	rue de Nanterre	101	10/26/2010	52	Mauvais	6.09	Très mauvais
1619610	de Pierrefonds boulevard	rue Guillaume	rue Geneviève	255	10/26/2010	56	Mauvais	5.3	Mauvais
1619611	de Pierrefonds boulevard	rue Blaignier	rue Guillaume	120	10/26/2010	50	Mauvais	5.03	Mauvais
1619614	de Pierrefonds boulevard	rue Grier	rue des Cageux	246	10/26/2010	59	Mauvais	5.72	Mauvais
1619615	de Pierrefonds boulevard	rue des Cageux	rue Dorsi	208	10/26/2010	63	Moyen	5.13	Mauvais
1619616	de Pierrefonds boulevard	rue Dorsi	rue Prével	147	10/26/2010	53	Mauvais	6.08	Très mauvais
1619754	de Pierrefonds boulevard	boulevard Saint-Charles	rue Blaignier	146	10/26/2010	55	Mauvais	5.59	Mauvais
1619832	de Pierrefonds boulevard	rue Forbes	boulevard Saint-Charles	295	10/26/2010	99	Excellent	2.31	Bon
1619857	de Pierrefonds boulevard	boulevard Pierrefonds	terrasse Richelieu	17	10/26/2010	100	Excellent	5.23	Moyen
1619859	de Pierrefonds boulevard	rue Becket	boulevard Pierrefonds	68	10/26/2010	93	Excellent	2.44	Bon
1619860	de Pierrefonds boulevard	terrasse Richelieu	rue Forbes	187	10/26/2010	99	Excellent	2.69	Moyen
1619867	de Pierrefonds boulevard	rue Sainte-Anne	rue Becket	122	10/26/2010	85	Bon	3.4	Moyen
1619908	de Pierrefonds boulevard	rue Paiement	rue Sainte-Anne	679	10/26/2010	97	Excellent	2.29	Bon
1619984	de Pierrefonds boulevard	boulevard de Pierrefonds	boulevard Jacques-Bizard	84	10/26/2010	94	Excellent	4.26	Moyen
1620085	de Pierrefonds boulevard	boulevard Saint-Jean	rue Harry-Worth	510	10/26/2010	90	Bon	2.76	Moyen
1620607	de Pierrefonds boulevard	rue René-Émard	boulevard Saint-Jean	203	10/26/2010	80	Moyen	5.16	Mauvais
1620664	de Pierrefonds boulevard	rue Fox	rue Aragon	25	10/26/2010	90	Bon	4.25	Moyen
1620666	de Pierrefonds boulevard	rue Aragon	rue Richmond	213	10/26/2010	86	Bon	2.63	Moyen
1620945	de Pierrefonds boulevard	rue Belleville	rue Fox	261	10/26/2010	88	Bon	2.69	Moyen
1620991	de Pierrefonds boulevard	rue Fredmir	rue Belleville	292	10/26/2010	97	Excellent	2.91	Moyen
1621787	de Pierrefonds boulevard	rue Parkinson	boulevard des Sources	196	10/26/2010	41	Mauvais	6.86	Très mauvais

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
1621788	de Pierrefonds boulevard	boulevard Gouin Ouest	rue Parkinson	109	10/26/2010	14	Très mauvais	9.1	Très mauvais
1621789	de Pierrefonds boulevard	boulevard Gouin Ouest	boulevard de Pierrefonds	65	10/26/2010	47	Mauvais	10.34	Très mauvais
1621797	de Pierrefonds boulevard	boulevard Gouin Ouest	boulevard de Pierrefonds	52	10/26/2010	52	Mauvais	6.4	Très mauvais
1623317	de Pierrefonds boulevard	boulevard Saint-Jean	rue Harry-Worth	64	10/26/2010	70	Moyen	4.71	Mauvais
1623318	de Pierrefonds boulevard	boulevard Saint-Jean	rue Harry-Worth	75	10/26/2010	70	Moyen	6.52	Très mauvais
4001903	de Pierrefonds boulevard	boulevard Saint-Jean	boulevard Saint-Jean	12	10/26/2010	100	Excellent	4.91	Moyen
4001906	de Pierrefonds boulevard	boulevard Jacques-Bizard	boulevard Jacques-Bizard	10	10/26/2010	75	Bon	3.71	Bon
4001907	de Pierrefonds boulevard	rue Esther-Blondin	rue Saint-Pierre	254	10/26/2010	86	Bon	2.52	Moyen
4001908	de Pierrefonds boulevard	rue Harry-Worth	rue Esther-Blondin	252	10/26/2010	64	Moyen	3.46	Moyen
4001909	de Pierrefonds boulevard	boulevard de Pierrefonds	boulevard Jacques-Bizard	79	10/26/2010	76	Moyen	3.95	Moyen
4001910	de Pierrefonds boulevard	rue Saint-Pierre	boulevard Jacques-Bizard	201	10/26/2010	98	Excellent	2.48	Bon
4001917	de Pierrefonds boulevard	boulevard Saint-Charles	boulevard Saint-Charles	15	10/26/2010	43	Moyen	9.51	Très mauvais
4002125	de Pierrefonds boulevard	boulevard des Sources	boulevard des Sources	14	10/26/2010	74	Bon	12.62	Très mauvais
4006207	de Pierrefonds boulevard	rue Athéna	rue Saint-Barnabas	187	10/26/2010	51	Mauvais	4.15	Moyen
4006208	de Pierrefonds boulevard	rue Athéna	rue Saint-Barnabas	188	10/26/2010	82	Bon	3.84	Moyen
4006211	de Pierrefonds boulevard	rue Saint-Barnabas	rue Dresden	151	10/26/2010	43	Mauvais	3.03	Moyen
4006212	de Pierrefonds boulevard	rue Saint-Barnabas	rue Saint-Barnabas	73	10/26/2010	75	Moyen	3.35	Moyen
4006213	de Pierrefonds boulevard	rue Saint-Barnabas	rue Dresden	77	10/26/2010	76	Moyen	3.59	Moyen
4006214	de Pierrefonds boulevard	rue Dresden	boulevard Westpark	128	10/26/2010	75	Moyen	3.29	Moyen
4006216	de Pierrefonds boulevard	rue Dresden	boulevard Westpark	128	10/26/2010	71	Moyen	3.25	Moyen
4006217	de Pierrefonds boulevard	boulevard Westpark	rue Bastien	163	10/26/2010	64	Moyen	2.82	Moyen
4006219	de Pierrefonds boulevard	boulevard Westpark	rue Bastien	164	10/26/2010	21	Très mauvais	4.04	Moyen
4006221	de Pierrefonds boulevard	rue Bastien	rue Coulon	106	10/26/2010	76	Moyen	2.41	Bon
4006222	de Pierrefonds boulevard	rue Bastien	rue Perron	321	10/26/2010	49	Mauvais	3.44	Moyen

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
4006223	de Pierrefonds boulevard	rue Coulon	rue Perron	214	10/26/2010	61	Moyen	3.86	Moyen
4006224	de Pierrefonds boulevard	rue Perron	rue Fredmir	332	10/26/2010	52	Mauvais	2.66	Moyen
4006225	de Pierrefonds boulevard	rue Perron	rue Fredmir	332	10/26/2010	65	Moyen	3.6	Moyen
4007383	de Pierrefonds boulevard	avenue du Chateau-Pierrefonds	rue Winnie-Wakefield	129	10/26/2010	93	Excellent	3.34	Bon
4007384	de Pierrefonds boulevard	avenue du Chateau-Pierrefonds	rue Winnie-Wakefield	129	10/26/2010	97	Excellent	3.12	Bon
4007386	de Pierrefonds boulevard	rue Winnie-Wakefield	rue Paul-Pouliot	75	10/26/2010	92	Excellent	5.53	Mauvais
4007387	de Pierrefonds boulevard	rue Winnie-Wakefield	rue Paul-Pouliot	74	10/26/2010	77	Bon	4.12	Moyen
4007388	de Pierrefonds boulevard	rue Paul-Pouliot	rue du Palomino	763	10/26/2010	82	Bon	5.02	Moyen

APPENDIX B: PIERREFONDS CASE STUDY 2015 DATA

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
1619533	de Pierrefonds boulevard	rue Prével	avenue du Chateau-Pierrefonds	381	10/5/2015	28	Très mauvais	6.17	Très mauvais
1619589	de Pierrefonds boulevard	rue de Nanterre	rue Grier	93	10/5/2015	33	Très mauvais	7.01	Très mauvais
1619608	de Pierrefonds boulevard	rue Geneviève	rue de Nanterre	101	10/5/2015	48	Mauvais	4.88	Mauvais
1619610	de Pierrefonds boulevard	rue Guillaume	rue Geneviève	255	10/5/2015	25	Très mauvais	6.15	Très mauvais
1619611	de Pierrefonds boulevard	rue Blaignier	rue Guillaume	120	10/5/2015	22	Très mauvais	6.36	Très mauvais
1619614	de Pierrefonds boulevard	rue Grier	rue des Cageux	246	10/5/2015	15	Très mauvais	7.75	Très mauvais
1619615	de Pierrefonds boulevard	rue des Cageux	rue Dorsi	208	10/5/2015	31	Très mauvais	5.98	Mauvais
1619616	de Pierrefonds boulevard	rue Dorsi	rue Prével	147	10/5/2015	22	Très mauvais	7.73	Très mauvais
1619754	de Pierrefonds boulevard	boulevard Saint-Charles	rue Blaignier	146	10/5/2015	29	Très mauvais	4.6	Mauvais
1619832	de Pierrefonds boulevard	rue Forbes	boulevard Saint-Charles	295	10/5/2015	83	Bon	2.89	Moyen
1619859	de Pierrefonds boulevard	rue Becket	boulevard Pierrefonds	68	10/7/2015	76	Moyen	3.1	Moyen
1619860	de Pierrefonds boulevard	terrasse Richelieu	rue Forbes	187	10/5/2015	73	Moyen	3.01	Moyen
1619867	de Pierrefonds boulevard	rue Sainte-Anne	rue Becket	122	10/7/2015	68	Moyen	4.05	Moyen
1619908	de Pierrefonds boulevard	rue Paiement	rue Sainte-Anne	679	10/7/2015	71	Moyen	2.54	Moyen
1619984	de Pierrefonds boulevard	boulevard de Pierrefonds	boulevard Jacques-Bizard	84	10/8/2015	59	Mauvais	4.19	Moyen
1620085	de Pierrefonds boulevard	boulevard Saint-Jean	rue Harry-Worth	510	10/7/2015	62	Moyen	2.83	Moyen
1620607	de Pierrefonds boulevard	rue René-Émard	boulevard Saint-Jean	203	10/7/2015	55	Mauvais	4.02	Moyen
1620664	de Pierrefonds boulevard	rue Fox	rue Aragon	25	10/7/2015	81	Bon	4.96	Mauvais
1620666	de Pierrefonds boulevard	rue Aragon	rue Richmond	213	10/7/2015	76	Moyen	2.85	Moyen
1620945	de Pierrefonds boulevard	rue Belleville	rue Fox	261	10/7/2015	72	Moyen	2.93	Moyen
1620991	de Pierrefonds boulevard	rue Fredmir	rue Belleville	292	10/7/2015	64	Moyen	2.89	Moyen
1621787	de Pierrefonds boulevard	rue Parkinson	boulevard des Sources	196	10/7/2015	26	Très mauvais	7.69	Très mauvais
1621788	de Pierrefonds boulevard	boulevard Gouin Ouest	rue Parkinson	109	10/7/2015	17	Très mauvais	5.64	Mauvais

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
1621789	de Pierrefonds boulevard	boulevard Gouin Ouest	boulevard de Pierrefonds	65	10/7/2015	18	Très mauvais	8.87	Très mauvais
1621797	de Pierrefonds boulevard	boulevard Gouin Ouest	boulevard de Pierrefonds	52	10/7/2015	18	Très mauvais	8.11	Très mauvais
1623317	de Pierrefonds boulevard	boulevard Saint-Jean	rue Harry-Worth	64	10/7/2015	51	Mauvais	4.29	Moyen
1623318	de Pierrefonds boulevard	boulevard Saint-Jean	rue Harry-Worth	75	10/8/2015	68	Moyen	6.34	Très mauvais
4001907	de Pierrefonds boulevard	rue Esther-Blondin	rue Saint-Pierre	254	10/7/2015	51	Mauvais	3.42	Moyen
4001908	de Pierrefonds boulevard	rue Harry-Worth	rue Esther-Blondin	252	10/7/2015	51	Mauvais	3.44	Moyen
4001909	de Pierrefonds boulevard	boulevard de Pierrefonds	boulevard Jacques-Bizard	79	10/7/2015	58	Mauvais	4.34	Moyen
4001910	de Pierrefonds boulevard	rue Saint-Pierre	boulevard Jacques-Bizard	201	10/7/2015	65	Moyen	3.04	Moyen
4006207	de Pierrefonds boulevard	rue Athéna	rue Saint-Barnabas	187	10/7/2015	39	Très mauvais	4.64	Mauvais
4006208	de Pierrefonds boulevard	rue Athéna	rue Saint-Barnabas	188	10/7/2015	57	Mauvais	4.4	Moyen
4006211	de Pierrefonds boulevard	rue Saint-Barnabas	rue Dresden	151	10/7/2015	47	Mauvais	3.59	Moyen
4006212	de Pierrefonds boulevard	rue Saint-Barnabas	rue Saint-Barnabas	73	10/7/2015	47	Mauvais	5.74	Mauvais
4006213	de Pierrefonds boulevard	rue Saint-Barnabas	rue Dresden	77	10/7/2015	43	Mauvais	4.3	Moyen
4006214	de Pierrefonds boulevard	rue Dresden	boulevard Westpark	128	10/7/2015	47	Mauvais	4.23	Moyen
4006216	de Pierrefonds boulevard	rue Dresden	boulevard Westpark	128	10/7/2015	54	Mauvais	4.05	Moyen
4006217	de Pierrefonds boulevard	boulevard Westpark	rue Bastien	163	10/7/2015	39	Très mauvais	3.07	Moyen
4006219	de Pierrefonds boulevard	boulevard Westpark	rue Bastien	164	10/7/2015	19	Très mauvais	4.9	Mauvais
4006221	de Pierrefonds boulevard	rue Bastien	rue Coulon	106	10/7/2015	50	Mauvais	2.68	Moyen
4006222	de Pierrefonds boulevard	rue Bastien	rue Perron	321	10/7/2015	28	Très mauvais	4.31	Moyen
4006223	de Pierrefonds boulevard	rue Coulon	rue Perron	214	10/7/2015	24	Très mauvais	4.18	Moyen
4006224	de Pierrefonds boulevard	rue Perron	rue Fredmir	332	10/7/2015	25	Très mauvais	3.15	Moyen
4006225	de Pierrefonds boulevard	rue Perron	rue Fredmir	332	10/7/2015	37	Très mauvais	3.65	Moyen
4007383	de Pierrefonds boulevard	avenue du Chateau-Pierrefonds	rue Winnie-Wakefield	129	10/5/2015	82	Bon	3.78	Moyen
4007384	de Pierrefonds boulevard	avenue du Chateau-Pierrefonds	rue Winnie-Wakefield	129	10/5/2015	50	Mauvais	4.6	Moyen

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
4007386	de Pierrefonds boulevard	rue Winnie-Wakefield	rue Paul-Pouliot	75	10/5/2015	42	Mauvais	8.76	Très mauvais
4007387	de Pierrefonds boulevard	rue Winnie-Wakefield	rue Paul-Pouliot	74	10/5/2015	22	Très mauvais	6.82	Mauvais
4007388	de Pierrefonds boulevard	rue Paul-Pouliot	rue du Palomino	763	10/5/2015	33	Mauvais	7	Mauvais
4010530	de Pierrefonds boulevard	boulevard de Pierrefonds	rue Athéna	64	10/7/2015	46	Mauvais	4.2	Moyen
4010531	de Pierrefonds boulevard	boulevard des Sources	rue Athéna	90	10/7/2015	45	Mauvais	4.12	Moyen
4010532	de Pierrefonds boulevard	boulevard des Sources	boulevard de Pierrefonds	155	10/7/2015	57	Mauvais	4.37	Moyen
4010533	de Pierrefonds boulevard	boulevard de Pierrefonds	rue Athéna	65	10/7/2015	50	Mauvais	3.07	Moyen
4010534	de Pierrefonds boulevard	boulevard des Sources	rue Athéna	91	10/7/2015	62	Moyen	3.54	Moyen
4010535	de Pierrefonds boulevard	boulevard des Sources	boulevard de Pierrefonds	155	10/7/2015	63	Moyen	4.05	Moyen
4010536	de Pierrefonds boulevard	rue Fredmir	rue Belleville	46	10/7/2015	59	Mauvais	5.91	Mauvais
4010537	de Pierrefonds boulevard	rue Fredmir	rue Belleville	45	10/7/2015	68	Moyen	3.59	Moyen
4010553	de Pierrefonds boulevard	boulevard Jacques-Bizard	rue Paiement	284	10/7/2015	61	Moyen	2.52	Moyen
4010837	de Pierrefonds boulevard	rue Richmond	rue René-Émard	388	10/7/2015	64	Moyen	3.88	Moyen

APPENDIX C: PIERREFONDS CASE STUDY 2018 DATA

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
4006216	de Pierrefonds boulevard	Dresden rue	Westpark boulevard	129	7/9/2018	51	Mauvais	5.47	Mauvais
4006214	de Pierrefonds boulevard	Dresden rue	Westpark boulevard	128	7/4/2018	38	Très mauvais	6.13	Très mauvais
4006221	de Pierrefonds boulevard	Bastien rue	Coulon rue	106	7/9/2018	27	Très mauvais	2.83	Moyen
4006223	de Pierrefonds boulevard	Coulon rue	Perron rue	214	7/9/2018	13	Très mauvais	6.14	Très mauvais
4010837	de Pierrefonds boulevard	Richmond rue	rue René-Émard	388	7/4/2018	65	Moyen	3.08	Moyen
4010553	de Pierrefonds boulevard	Jacques-Bizard boulevard	Paiement rue	284	7/4/2018	34	Très mauvais	3.56	Moyen
1619908	de Pierrefonds boulevard	Paiement rue	Sainte-Anne rue	678	7/9/2018	57	Mauvais	2.9	Moyen
1619867	de Pierrefonds boulevard	Sainte-Anne rue	Becket rue	123	7/9/2018	61	Moyen	3.495	Moyen
4010537	de Pierrefonds boulevard	Fredmir rue	de Pierrefonds boulevard	45	7/9/2018	49	Mauvais	3.39	Moyen
4010536	de Pierrefonds boulevard	Fredmir rue	de Pierrefonds boulevard	47	7/4/2018	29	Très mauvais	5.27	Mauvais
4010532	de Pierrefonds boulevard	des Sources boulevard	Non-nommé voie	156	7/4/2018	53	Mauvais	4.57	Mauvais
4010535	de Pierrefonds boulevard	des Sources boulevard	Non-nommé voie	155	7/9/2018	43	Mauvais	3.66	Moyen
4010534	de Pierrefonds boulevard	Non-nommé voie	Non-nommé voie	92	7/9/2018	48	Mauvais	3.98	Moyen
4006211	de Pierrefonds boulevard	Saint-Barnabas rue	Dresden rue	151	7/9/2018	19	Très mauvais	4.25	Moyen
4006207	de Pierrefonds boulevard	rue Athéna	Saint-Barnabas rue	188	7/9/2018	18	Très mauvais	5.55	Mauvais
4010533	de Pierrefonds boulevard	Non-nommé voie	rue Athéna	66	7/9/2018	20	Très mauvais	4.23	Moyen
4010531	de Pierrefonds boulevard	Non-nommé voie	Non-nommé voie	91	7/4/2018	40	Très mauvais	4.42	Moyen
4006208	de Pierrefonds boulevard	rue Athéna	Saint-Barnabas rue	188	7/4/2018	46	Mauvais	5.33	Mauvais
4010530	de Pierrefonds boulevard	Non-nommé voie	rue Athéna	65	7/4/2018	36	Très mauvais	5.62	Mauvais
4007388	de Pierrefonds boulevard	Paul-Pouliot rue	du Palomino rue	762	7/30/2018	55	Mauvais	6.48	Très mauvais
4007386	de Pierrefonds boulevard	Winnie-Wakefield rue	Paul-Pouliot rue	75	7/9/2018	48	Mauvais	8.9	Très mauvais
4007383	de Pierrefonds boulevard	avenue du Chateau-Pierrefonds	Winnie-Wakefield rue	129	7/9/2018	53	Mauvais	4.27	Moyen
4007387	de Pierrefonds boulevard	Winnie-Wakefield rue	Paul-Pouliot rue	74	7/4/2018	14	Très mauvais	8.04	Très mauvais

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
4007384	de Pierrefonds boulevard	avenue du Chateau-Pierrefonds	Winnie-Wakefield rue	129	7/4/2018	58	Mauvais	5.31	Mauvais
4006225	de Pierrefonds boulevard	Perron rue	Fredmir rue	331	7/4/2018	34	Très mauvais	4	Moyen
4006224	de Pierrefonds boulevard	Perron rue	Fredmir rue	332	7/9/2018	8	Très mauvais	4.03	Moyen
4006222	de Pierrefonds boulevard	Bastien rue	Perron rue	321	7/4/2018	21	Très mauvais	5.37	Mauvais
4006213	de Pierrefonds boulevard	Saint-Barnabas rue	Dresden rue	77	7/4/2018	33	Très mauvais	4.72	Mauvais
4006212	de Pierrefonds boulevard	Saint-Barnabas rue	Saint-Barnabas rue	73	7/4/2018	49	Mauvais	5.87	Mauvais
4002125	de Pierrefonds boulevard	des Sources boulevard	des Sources boulevard	14	7/9/2018	73	Moyen	11.34	Très mauvais
1619857	de Pierrefonds boulevard	Pierrefonds boulevard	Richelieu terrasse	17	7/9/2018	47	Mauvais	1.01	Excellent
1619860	de Pierrefonds boulevard	Richelieu terrasse	Forbes rue	187	7/9/2018	58	Mauvais	2.92	Moyen
1619832	de Pierrefonds boulevard	Forbes rue	Saint-Charles boulevard	295	7/9/2018	67	Moyen	2.705	Moyen
4001917	de Pierrefonds boulevard	Saint-Charles boulevard	Saint-Charles boulevard	16	7/4/2018	98	Excellent	4.83	Mauvais
4001910	de Pierrefonds boulevard	Saint-Pierre rue	de Pierrefonds boulevard	201	7/9/2018	57	Mauvais	3.44	Moyen
4001909	de Pierrefonds boulevard	de Pierrefonds boulevard	Jacques-Bizard boulevard	79	7/9/2018	56	Mauvais	4.74	Mauvais
1620085	de Pierrefonds boulevard	de Pierrefonds boulevard	Harry-Worth rue	510	7/9/2018	45	Mauvais	3.005	Moyen
4001908	de Pierrefonds boulevard	Harry-Worth rue	Esther-Blondin rue	252	7/9/2018	36	Très mauvais	4.52	Mauvais
4001907	de Pierrefonds boulevard	Esther-Blondin rue	Saint-Pierre rue	255	7/9/2018	43	Mauvais	3.13	Moyen
1623317	de Pierrefonds boulevard	Saint-Jean boulevard	de Pierrefonds boulevard	65	7/4/2018	44	Mauvais	3.58	Moyen
1620607	de Pierrefonds boulevard	rue René-Émard	Saint-Jean boulevard	203	7/9/2018	38	Très mauvais	4.28	Moyen
1620991	de Pierrefonds boulevard	de Pierrefonds boulevard	Belleville rue	292	7/9/2018	48	Mauvais	3.2	Moyen
1620945	de Pierrefonds boulevard	Belleville rue	Fox rue	261	7/9/2018	51	Mauvais	3.015	Moyen
1620664	de Pierrefonds boulevard	Fox rue	Aragon rue	25	7/9/2018	75	Moyen	4.55	Mauvais
1620666	de Pierrefonds boulevard	Aragon rue	Richmond rue	213	7/9/2018	53	Mauvais	3.75	Moyen
1619984	de Pierrefonds boulevard	de Pierrefonds boulevard	Jacques-Bizard boulevard	84	7/30/2018	39	Très mauvais	4.58	Mauvais
1619859	de Pierrefonds boulevard	Becket rue	Pierrefonds boulevard	68	7/9/2018	67	Moyen	3.145	Moyen

ID_TRC	Rue	De	A	Longueur	DateReleve	Indice PCI	Etat PCI	Indice IRI	Etat IRI
1619611	de Pierrefonds boulevard	Blaignier rue	Guillaume rue	120	7/9/2018	17	Très mauvais	8.185	Très mauvais
1619754	de Pierrefonds boulevard	Saint-Charles boulevard	Blaignier rue	147	7/9/2018	32	Très mauvais	6.49	Très mauvais
1619616	de Pierrefonds boulevard	Dorsi rue	de Riva-Bella rue	147	7/9/2018	21	Très mauvais	7.815	Très mauvais
1619533	de Pierrefonds boulevard	de Riva-Bella rue	avenue du Chateau-Pierrefonds	381	7/9/2018	18	Très mauvais	7.43	Très mauvais
1619615	de Pierrefonds boulevard	des Cageux rue	Dorsi rue	208	7/9/2018	24	Très mauvais	9.03	Très mauvais
1619610	de Pierrefonds boulevard	Guillaume rue	rue Geneviève	255	7/9/2018	17	Très mauvais	8.985	Très mauvais
1619608	de Pierrefonds boulevard	rue Geneviève	de Nanterre rue	102	7/9/2018	28	Très mauvais	7.655	Très mauvais
1619589	de Pierrefonds boulevard	de Nanterre rue	Grier rue	93	7/9/2018	20	Très mauvais	12.375	Très mauvais
1619614	de Pierrefonds boulevard	Grier rue	des Cageux rue	247	7/9/2018	12	Très mauvais	10.075	Très mauvais

APPENDIX D: LCC-BASED OPTIMIZED M&R DETAILED TIMETABLE

Corridor number	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Minor Rehab.	Major Rehab.	Reconstruction	Total
Corridor 1	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	1	3	1	0	4
Corridor 2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	2
Corridor 3	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0	4
Corridor 4	0	0	0	0	0	0	2	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2	1	0	3
Corridor 5	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	3	0	0	3
Corridor 6	0	0	0	0	0	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	4	0	0	4
Corridor 7	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	1	2	0	3
Corridor 8	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	1	2	0	3
Corridor 9	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	4	0	0	4
Corridor 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	1
Corridor 11	0	0	0	0	0	0	0	2	0	0	1	0	0	0	1	0	0	0	0	0	0	2	1	0	3
Corridor 12	0	0	0	0	0	0	2	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2	1	0	3
Corridor 13	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	2
Corridor 14	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	2
Corridor 15	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	2
Corridor 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	1
Corridor 17	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	4	0	0	4
Corridor 18	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
Corridor 19	0	1	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	1	0	3
Corridor 20	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	1
Corridor 21	0	0	0	0	0	0	2	0	0	1	0	0	0	0	1	0	0	0	0	0	0	2	1	0	3
Corridor 22	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	1	1	0	2
Corridor 23	0	0	0	0	0	0	2	0	0	0	0	0	1	0	1	0	0	0	0	1	0	3	1	0	4
Corridor 24	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	1	0	2
Corridor 25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	1
Corridor 26	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	1
Corridor 27	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	1
Corridor 28	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	1	1	0	2
Corridor 29	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Corridor 30	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	1
Corridor 31	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	2
Corridor 32	0	0	0	0	0	3	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	2	0	1	3
Corridor 33	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	2
Corridor 34	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	2
Corridor 35	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	2
Corridor 36	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	2
Corridor 37	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	1	2	0	3
Corridor 38	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0	2
Corridor 39	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	1	2	0	3