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A Risk-Based Multi-Objective Modeling Approach to the Preventive Maintenance Process of Roof Waterproofing System at Airports

By

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Dedication Page

To my loving family and friends.

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A Risk-Based Multi-Objective Modeling Approach to the Preventive Maintenance Process of Roof Waterproofing System at Airports.

Bahaa Jamal Shehab

ABSTRACT

This study adopted a mixed research design in order to derive a risk-minimizing preventive maintenance strategy for structural roofing leakage problems. The purpose of this study is to: (a) determine current waterproofing systems and components of concrete roofs at airports, (b) explore frequently used techniques to design optimal preventive maintenance policies, and (c) derive an optimal preventive multi-objective risk-based maintenance strategy via simulation that can diminish failure costs, thereby decreasing the system's overall maintenance costs. Unique to the simulation presented in this thesis is the inclusion of external influences on failure probability via a predictive model derived using a random forest machine learning strategy. A case study on a prototype airport serves as the platform to test this simulation methodology. The results of the simulation reveal the prognostic influence of several maintenance strategies on the total risk-based cost of the waterproofing system. These outcomes showed a negative impact on the reduction of the failure-risk costs, and eventually augmented the overall cost. Thus, demonstrating that for assets whose failure is primarily dictated by external factors, a corrective maintenance strategy can be optimal.

Keywords: Leakage, Failures, Costs, Roofs, Airport, Multi-objective, Risk-based, Maintenance Strategies, Preventive, Optimization.

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Chapter 1

Introduction

Maintenance studies are desirable research in today's highly competitive and tech-based facilities. The main focus is on cost reduction in most industries and facilities, thus making this subject an interesting study for researchers and managers alike (Camci, 2015). Even though maintenance is a non-value added process in the industry, it is undeniable that it plays a significant role in the asset management process (Ab-samat, Jeikumar, Basri, & Harun, 2012). Based on that, the main objective of facility managers is to make sure that the operation costs are low while preserving the same quality and reliability of the whole system. This makes implementing the perfect maintenance strategy with a low cost, the key to any successful facility. It is also essential to recognize that maintenance is not like any ordinary stand-alone process, but a complex operation which interacts with inventory and personnel management along with proper management and production planning (Camci, 2015).

In general, we have two types of maintenance: reactive maintenance and proactive maintenance. Reactive maintenance is also called corrective maintenance and refers to a failure that occurs during the operations, which requires facility managers to work on fixing the problem that caused the issue. In contrast, “Prevention is better than cure” (Ab-samat et al., 2012). Proactive maintenance is the process where management includes inspections on all assets and maintains them properly to avoid problems. This type of maintenance is divided into two categories: the first is condition-based maintenance (CBM), whereby machines are monitored and fixed only before projected failure. The second category is preventive maintenance, which involves doing proper maintenance at regularly scheduled intervals to make sure that the asset is well maintained, properly working, and forecast to have a prolonged life span.

Recently, mathematical models have helped to design the most desirable preventive maintenance systems in most facilities. Indeed, it is adequate to model the system under a set of specific constraints and operating modes, depending on the case at hand (Rivera Torres, Serrano Mercado, Llanes Santiago, & Anido Rifón, 2018), facility managers should also take into consideration the complexity of some industries in chaotic uncertain environments. These models must integrate deterministic procedures (such as crew scheduling requirements) with probabilistic maintenance failure events and phenomena that might hinder the delivery of timely maintenance. In other words, it is recommended to enforce a context-specific risk-based model for a better productive future. Recently, automation tools and data mining methods have been basic needs for maintenance industries. They provide convenient approaches to millions of historical data entries and thus allow for simulation models that provide the best maintenance strategy for a given policy (Blakeley, Bozkaya, Cao, Hall, & Knolmajer, 2003; Romanowski & Nagi, 2001).

One example of a setting in which reactive and proactive maintenance activities combine with external controlled and uncontrolled events is waterproofing at airports. Waterproofing, by itself, is a very complex and sensitive asset. Maintaining it requires specialized technicians, expensive equipment and materials, clean and well leveled overall area conditions, non-humid clear weather, etc. Moreover, what makes waterproofing in this context more complicated is the airport facility. Working at airports means handling extreme security measures, increased failure cost, different electromechanical equipment deficiencies, accessories on rooftops with many maintenance personnel visiting them, and unique design accommodating the roof plan. Waterproofing at airports has been a significant issue throughout the years. Usually, its failure cost is high since it might end up disrupting the process of departures and arrivals at the airports.

1.1 Research Questions

1. Does the introduction of a preventive maintenance strategy have a positive impact on total risk-based costs when compared to that of a “run-to-failure” strategy?

1.2 Significance of the Dissertation

The main objective of this thesis is to reduce the risk-based failure cost associated with water leakage and balance it through an optimal preventive maintenance system. It would then tackle a multi-objective maintenance problem and can withstand both certain and uncertain environments at airports.

Chapter 2

Literature Review

2.1 Waterproofing: A shield against water penetration

“Waterproofing is a coating or membrane applied to a surface, such as foundation wall, to prevent the intrusion of water under pressure; materials may include asphalt, felt, tar, or various synthetic membranes” (Mydin, Nawi, & Munaaim, 2017, p. 4). In their article, Mydin, Nawi, and Munaaim (2017) focused on listing waterproofing failure types, elaborating on their effect on the concrete structure, and providing remedial solutions for structural buildings. Water is the main reason for defective concrete structures. Due to its chemical and flow-free composition, water allows itself to easily penetrate several areas through chemically decomposing materials in the presence of oxygen and carbonate (Mydin et al., 2017). Thus, the existence of waterproofing is essential. Figures 1-4 show different water intrusion effects on concrete and portray the different types of concrete failures, and Figure 5 describes all types of cracks from humidity and water incursion.

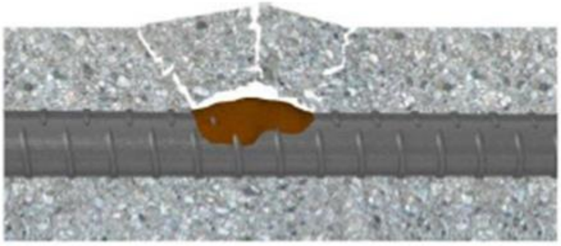


Figure 1: Corrosion on the reinforcements due to the water chemical reaction with steel (Mydin et al., 2017).

Figure 2: Razed paint structure and heavy equipment corrosion in mechanical rooms (Mydin et al., 2017).

Figure 3: Major horizontal and vertical cracks on a concrete base foundation (Mydin et al., 2017).

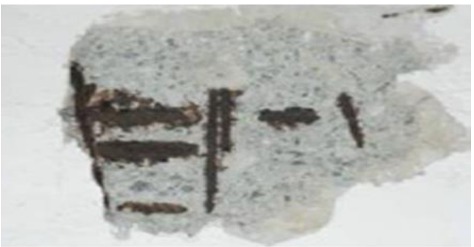


Figure 4: Reinforced ceiling concrete deterioration(Mydin et al., 2017).

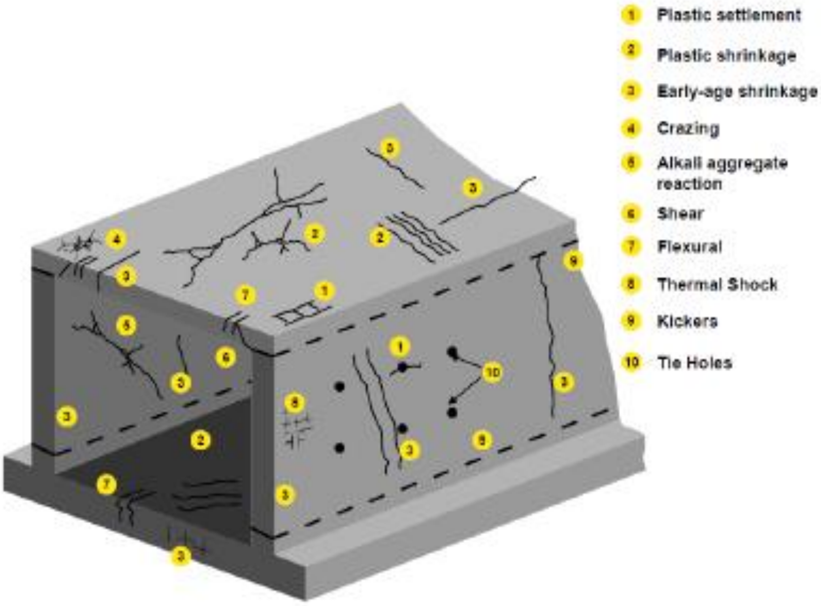


Figure 5: Different types of cracks caused by water reactions with the concrete(Mydin et al., 2017).

Even with high-quality, constructed buildings, no matter their age, their structure is vulnerable to humidity, rain, and climate change. Thus the availability of waterproofing is the only asset that can prevent water from complete penetration (Mydin et al., 2017). Mydin et al. (2017) also mentioned that it is well advised to have a well-constructed structure for waterproofing to have its utmost effectiveness against water leakage. Moreover, prior to the installation of waterproofing, the moisture on the finishing screed and concrete should be dealt with. Its existence between both assets will turn into water vapor, which might cause dampness and deterioration of the waterproofing membrane, and thus penetrating the concrete structure or cement screed. They also mentioned the need for high quality, highly dedicated, experienced, and professional individuals to carry out the waterproofing installation. There exist many types of waterproofing that are used in different areas based on their specifications and owner desires such as, the PVC coated membrane, polyurethane liquid membrane, rubber membranes, and many more (Constro Facilitator, 2020). All waterproofing types are divided into three main components: liquid membrane, sheet-based membrane, and cementitious. Table 1 presents the different components of waterproofing with all their specifications, pros, and cons.

Table 1: Summary of Waterproofing Types(Constro Facilitator, 2020).

Type of Waterproofing	**Characteristics and Specialties**	**Advantages**	**Disadvantages**
Liquid Waterproofing Membrane	Liquid applied membranes are useful on the site where the liquid sprayed can set and form a water-impermeable layer. They are also helpful in tight areas where sheet based waterproofing membrane is inadequate.	It resists UV radiations, bonds with structures, has a low-cost implementation, can breathe, withstands some pressure, is easy to use, repair, and maintain.	It can be easily damaged, is very sensitive to humidity and climate change, requires ongoing surveillance and supervision, and has a short lifespan.
Sheet-Based Waterproofing Membrane	Consists of thermoset and thermoplastic materials. Thermoset membranes can be either vulcanized or non-vulcanized material and performed as rubberized sheets. It often comes as sheet rolls. This system is usually applied through heat or adhesive on the concrete or cement screed.	It is not as vulnerable as other systems, allows heat resistance board and ballast to be placed on top for protection, has elongation benefits that make it better for structural movements, weather changes, humidity, and rain, and is easy to install.	It is tricky in tight areas, requires technically professional technicians, and high implementation cost.

Cementitious Waterproofing	This type of waterproofing is used to close active cracks, leaks, coves, penetrations, and fillets. It can be used on both concrete and masonry surfaces. This type is best implemented in closed areas and basements.	It is inexpensive and easy to apply.	It has no elasticity and cannot tolerate crack movement.

All this said, waterproofing itself tends to deteriorate in time as well, if not attended. Mainly, this thesis focuses on EPDM sheet-based waterproofing. In general, EPDM is a compound rubber geomembrane made of three monomers: ethylene, propylene, and diene. Both the propylene and ethylene serve as the carbon structure of the EPDM. The propylene has a 30-50% carbon chain structure, while 50-70% for ethylene. However, both carbon compounds must be cross-linked; otherwise, they might move independently, which brings us to the last monomer. Diene is the compound responsible for the cross-linking; it serves as the backbone of the entire

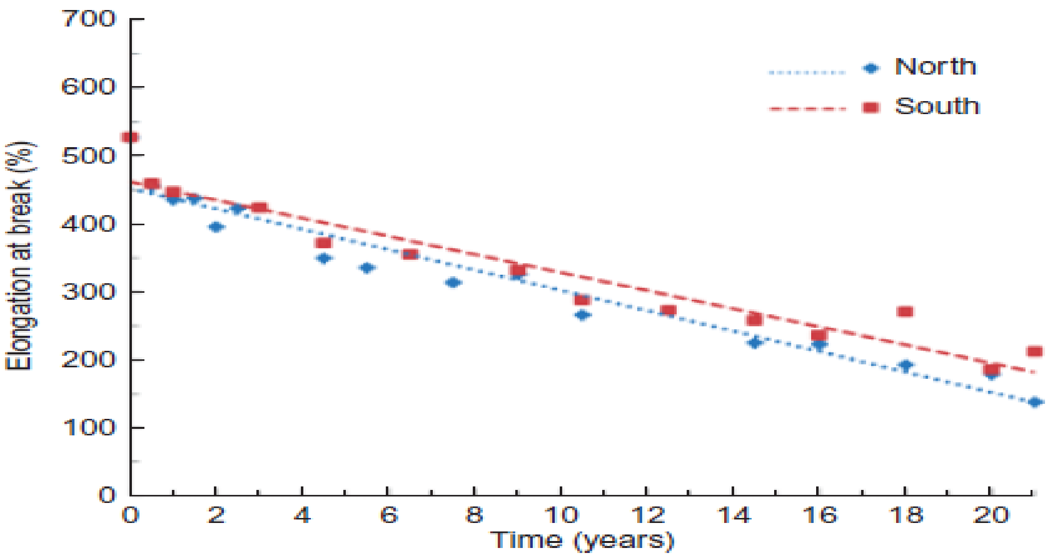


Figure 6: Graph representing the decrease in the EPDM durability to withstand elongation to break (%) in 21 years of time(years) for both northern and southern slopes(Noval et al., 2014).

carbon structure. All these compounds are subject to failure, especially diene monomer, as it is the most vulnerable to ultraviolet radiation (Noval et al., 2014).

In their article, Noval et al. (2014) studied the El Boquerón reservoir located in La Laguna, Tenerife, Spain. This study focused on the EPDM sheet-based waterproofing system and carefully studied its durability for 21 consecutive years under constant humidity. One of the most critical root causes in the study was the ultraviolet radiation and how its impact on the EPDM structure. The reservoir understudy had a relatively high UV index during clear sky weather ranging between Elongation 6.5 and 8.5, and an average temperature of 21.3 °C. It was divided into two separate areas: the northern slope and the southern slope with a higher ultraviolet index detected relative to the latter. Samples from both slopes were taken frequently to study the ultraviolet malignance on EPDM. Consequently, after 21 years, the results were as follows:

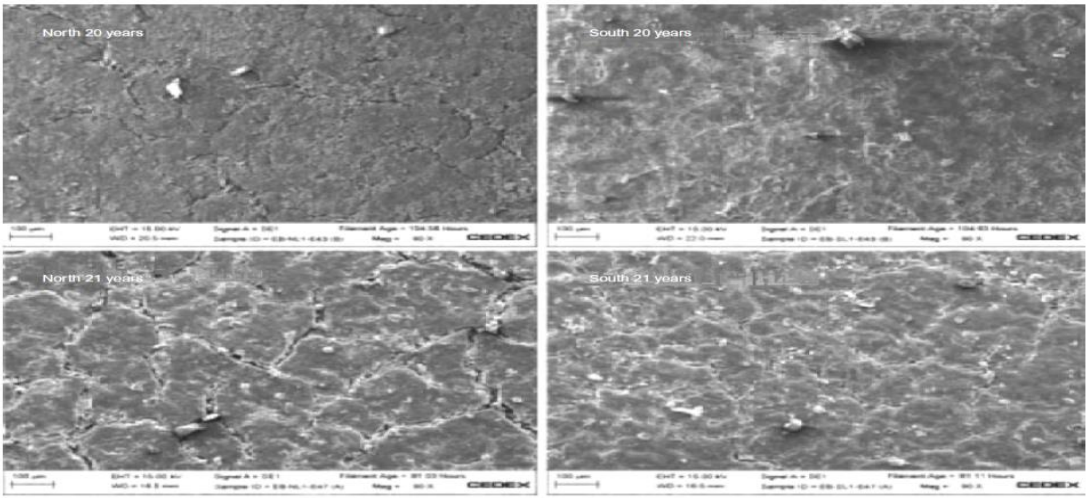


Figure 7: Excessive microcracks were visible under microscopic vision in year 20, which augmented in year 21(Noval et al., 2014).

1) Elongation at break– a measure of the capability of the material to withstand stretching before breaking or failing– which was initially at 527%, decreased to 212% for the southern slope, and 138% for the northern one (as shown in Figure 6).
2) The thickness of the southern samples was thicker than those of the northern.
3) The folding at low-temperature test results had a positive review, and both samples did well.

4) Microcracks augmented at a vast rate between the years 20 and 21 for both the northern and southern slope samples, keeping in mind that the northern was damaged more than the southern (as shown in Figure 7).

Another intriguing study on EPDM failures and maintenance was that of Rossiter et al. (1991). This study elaborated on the technical EPDM waterproofing roofing maintenance system at several military air force base with low-sloped roofing systems, to inspect the condition and quality of the waterproofing system and its routine preventive maintenance. Most of the EPDM systems installed consisted of the sheet itself, insulation boards to provide a shield from ultraviolet sun radiations, and ballast materials spread on top to keep them protected. The study was conducted on fifteen USAF (United States Airforce) roofing installations in 11 states that were visited, and 61 EPDM roofs of a young age were inspected. Each area had a thorough inspection of the condition of the EPDM, where the inspectors provided a general assessment on the asset and provided a subjective condition rating on the entire area based on several key factors and quality assessment elements. During the inspection, the EPDM defects were taken into consideration to rate the asset such as signs of deterioration (crazing, cracking, discoloration, or extreme abrasion) and flexibility of the rubber material judged by pulling, pushing, or bending. Many reasons were given to emphasize more on the cause of problems like weather conditions, abuse, poor workmanship, and improper maintenance. Table 2 demonstrates the elaborate condition rating system that was used in the study. Considering that most of the inspected assets were young, satisfactory results were obtained from the inspection. About half of the total inspected EPDM roofs were found in good condition, and another third displayed only minor defects, which were very limited in scope and were readily reparable with routine maintenance. The remaining had numerous significant defects, which questioned the maintenance policy plan implemented upon the roofs. None of the areas had a poor condition, where immediate replacement was needed.

Table 2:Condition rating order and basis.

Rating	Basis

5	Excellent condition, no defect was observed, and proper maintenance performance.
4	Good condition, some defects were observed that required routine preventive maintenance that might affect the durability of the EPDM, causing future problems, but would not damage the functionality of the EPDM system.
3	Fair condition, numerous defects were found on the roof that required immediate preventive maintenance.
2	Bad condition, numerous major defects found that require immediate attention, which might end up with failure. This condition requires more than preventive maintenance to solve the problem.
1	Poor condition, significant defects that require replacing the whole roof to solve the problem.

2.2 Preventive Maintenance

Essentially, the first step for a useable preventive maintenance plan in airports is the assessment phase. This means that the facility manager should study the infrastructure of the entire system, its components, well-being, life span, priorities, and condition (Ploeger, Chapman, Peshkin, Speidel,2015). Based on the given resources, he or she should come up with the perfect prognostic strategy to decrease failure costs and ensure a prolonged life span of all assets.

Proactive maintenance in public buildings is obligatory, especially in airports. Like any other public figure, the airport should meet several requirements as put by the client to retain the perfect image set by the country. Such requirements can be as follows:

1) Safety Measures: Facility management should ensure safe airports for pilots, employees, and commuters when entering the facility environment.
2) Quality and Appearance: Quality measures define airports from one another. High-quality standards tend to provide core-competencies and better appearance as a public building.
3) Contractual Obligations: Any airport must abide by State/Federal requirements airports to stay operational.
4) Economics: A facility manager should come up with a cost-effective maintenance strategy to decrease failure costs and ensure a prolonged life span of all assets. This requires specifying a reasonable budget for both proactive and reactive maintenance based on the required objectives.
5) Accessibility: It is crucial to provide safe access to the airport for all users, pilots, and employees. More importantly, facility managers should maintain safe and efficient maintenance access to all assets for better maintenance operations.

However, with such measures, proactive maintenance by itself can be costly, while reactive maintenance problems come with extra enormous subsequent expenses. Thus, with the given resources, operations management should focus on a maintenance strategy that effectively balances all needs. Thus, an optimal maintenance strategy is one that provides a strategic maintenance schedule that best suits the industry’s objectives with the given resources and lowers failure

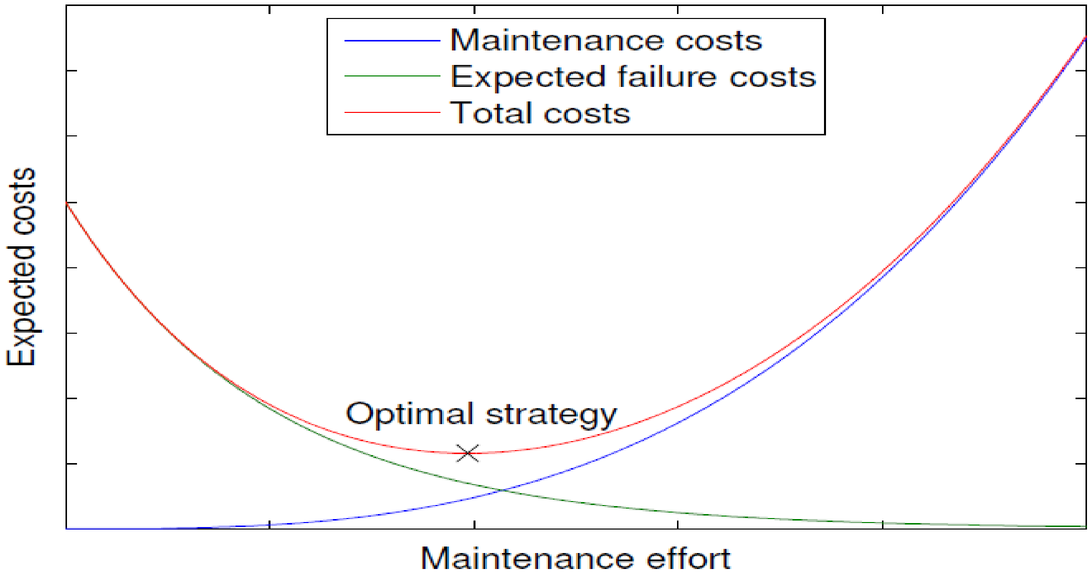


Figure 8 Variation of the total cost in terms of maintenance efforts(Nielsen & Sørensen, 2014).

consistency(Nielsen & Sørensen, 2014). This would eventually minimize the total cost of maintenance to reach its minimum. Figure 8, the total cost of maintenance depends on the maintenance efforts itself. Without preventive maintenance, a plethora of corrective maintenance activities would exist, causing a high maintenance cost. Enormous preventive maintenance efforts would diminish the failure costs but result in an even higher total maintenance cost. However, implementing an optimal preventive maintenance strategy would eventually lower the corrective maintenance to a certain acceptable range, and result in the best maintenance cost outcome.

2.3 Risk-Based and Reliability Centered Maintenance

As a general overview, this literature review will focus on two types of maintenance strategies: multi-objective risk-based maintenance (RBM) and reliability-centered maintenance (RCM). Both strategies have proven to be very efficient and effective in recent years. For the risk-based maintenance strategy, scientists tend to focus on the root problems, their failures, and subsequent risks of the industry's assets. Which would, eventually, help organize the optimal maintenance strategy required, achieving the objectives given by the upper management. On the other hand, a reliability-centered maintenance strategy focuses on the stability, well-being, and impetus of the asset. It starts by assessing and analyzing the equipment downtime, highlighting the consequences of such a problem, and then carrying out an efficient optimization strategy to help solve the situation. So, with the help of several probabilistic tools and algorithms, researchers can reach a positive outcome as presented in several previous articles (Abdulwhab et al., 2010; Dey, 2001; Dinmohammadi, 2019; Inazumi, Sekitani, Chae, & Shishido, 2017; Neves, Frangopol, & Petcherdchoo, 2006; Rivera Torres et al., 2018).

2.3.1 RBM Strategy

In general, a risk-based maintenance strategy is a technique that analyzes the possible effects of the risks and suppresses them (Inazumi et al., 2017). Moreover, it provides several approaches for an exemplary and efficient maintenance system, not just through understanding the probability of failures, but their consequences as well (Lounis, 2015). This part provides a review of previous articles that illustrates the importance of a risk-based probabilistic maintenance optimization in a stochastic environment. Essentially, implementing a new prognostic maintenance strategy requires a thorough research study, in which several scientists tended to have their methodology and probabilistic models based on the case studies' historical data (Ab-samat et al., 2012).

"In general, risk is a combination of two factors: the probability of occurrence of a failure, and the magnitude of the consequences of the failure"(Dinmohammadi, 2019, p. 4). A risk-based maintenance management methodology encompasses both the probability of failure and the consequences of failure. Based on that, risk-based analysis is the system that analyzes the likelihood of several catastrophes, determines the most critical ones, and then implements a preventive maintenance program to diminish them with the available resources(Dinmohammadi, 2019). Through time, studies have provided several tools and techniques that helped tackle risk-based problems, including fault tree analysis (FTA), root cause analysis (RCA), minimal cut sets, event tree analysis, failure mode and effects analysis, failure mode, and effects and criticality analysis (FMECA), reliability block diagram, Weibull analysis, design for reliability, physics of failure method, first-order reliability method, second-order reliability method, Bayesian reliability, and human reliability assessment, among others (Dinmohammadi, 2019). In her article, Dinmohammadi (2019) used the trains of a Scottish railway system as a case study. She introduced the Risk-based inspection and maintenance methodology (RBI&M) to minimize the failure cost and apply a better preventive maintenance structure. She first considered a mechanical part of the train and presented its components' functions. Then she showed potential failure modes through historical data, identified the root causes for each, and determined the total probability of failure. Later, she presented their consequences on the whole system, devised risk measures, and then designed a better inspection methodology to reduce inspection time and cost. So compared to the previous ordinary preventive maintenance scheduling, the use of the RBI&M method was somewhat more effective, serviceable, cheaper, and safer for the whole railway process.

Similarly, Dey (2001), looking at maintenance of oil pipelines, examined the losses incurred with the excessive inspection time needed to find the leakage problems of pipelines and thus resulting in a high maintenance cost. He first presented the importance of pipelines and their vitality to transfer hydrocarbons, compared to standard transportation tools like trucks and tankers. Nevertheless, pipeline failure can be catastrophic. In this domain, Dey’s (2001) main optimization objective was to introduce an efficient, safe, flexible, and reliable inspection methodology, with the help of both the decision support system(DSS) and Analytical Hierarchy Process(AHP) as tools. As for the method, Dey (2001) divided the pipeline into several spans based on their location and specifications, explained the root causes of the failures through historical data used the AHP to demonstrate the risk structure of the entire system in order to deduce the probability of all designated failures. Figure 9 shows the AHP risk structure. Dey (2001) then compared the risk factors using the pair-wise comparison tool to identify the failure possibility of all the pipeline stretches, and then deduced a better inspection and maintenance management strategy. As a result, during the application, both the maintenance, inspection, and failure costs were reduced(Dey, 2001).

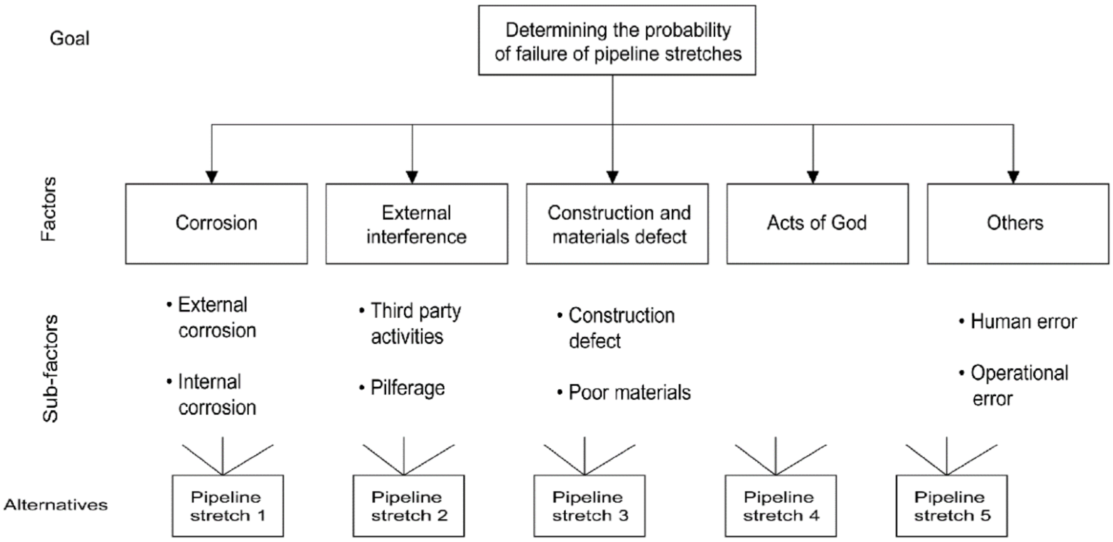


Figure 9: The risk-based Analytical Hierarchy Process model(Dey, 2001).

 Another Risk-Based Maintenance strategy is the multi-objective optimization method. Applying this method in their article on silane maintenance of bridges, Neves et al. (2006) aimed to reach the best combination of condition, safety, and cost. This is achieved through satisfying all performance constraints of deteriorating bridges during a specified time horizon, under multi-objective based maintenance, and then compared to a single-objective maintenance strategy (Neves et al., 2006). They first used single-objective models to solve problems related to the condition, safety, and cost, each separately. Then created a stochastic problem structure and implemented, concurrently, a function with the worst percentile of condition index, safety index, along with a high accumulated single maintenance type cost. Then they applied a multi-objective maintenance model that solved all three aspects at the same time. Keeping in mind, the historical data was based on expert opinion, previous studies, and cost-based documents. Then, by using genetic algorithms and Latin hypercube sampling, they compared the multi-objective maintenance strategy's condition, safety, and cost, to that of the single maintenance type. And eventually, the multi-objective optimization had a better impact on all three aspects. Another example of a multi-objective optimization article was Lounis article (2016). In his article, like Neves et al.'s article (2006), the focus was to improve the condition of the asset while reducing the maintenance and user costs. Doing so minimizes both the probability and consequences of the projected property failures. Lounis (2016) focused on a case study on concrete bridge decks that had corrosion as the most haphazard and customary reason for their deterioration. Associated failures would severely damage the serviceability and condition of the entire bridge, followed by a massive impact on maintenance and user cost. In this type, engineers tend to get flummoxed by the complexity of handling bridge decks maintenance, since closing down an operating bridge can be a highly complicated task that requires the approval of the authority (Lounis, 2015). Moreover, organizing a dedicated and professional team of technicians to handle maintenance objectives is a must because of the sophisticated technical steps required. The techniques used in the article were based on three models: multi-objective optimization, qualitative condition assessment, and a qualitative deterioration predictive model. First, Lounis (2015), like Rossiter et al. (1991), evaluated the condition of concrete decks and rated them based on several criteria like contamination, corrosion, and several other defective categories. The condition rating provided had a more explicit order of the bridge deck condition than that of Rossiter et al. (1991). Table 3 shows the condition assessment table of 7 distinct conditions. Then, by using Bogdanoff's Cumulative Damage Model, Lounis (2015) determined the life span and condition of each concrete deck based on the probability of the accumulation process due to damage. After this, he uses the multi-objective approach, where he listed all the objectives that are needed to make the system optimal, such as safety improvement, cost reduction, etc. Eventually, the author implemented the previous strategies on a case study of 100 concrete decks, and the results obtained were positive and highly effective. Moreover, the best maintenance strategy was implemented to nearly achieve the desired optimal solutions and results.

2.3.2 RCM Strategy

On the other hand, other articles encourage the adaptation of reliability-centered maintenance (RCM) in industries. Generally, RCM is usually atypical worldwide; however, its implementation on power generating assets would help reach the desired optimal outcomes, such as better control and decision making, longer equipment uptime, and lower costs(Abdulwhab et al., 2010). In their article, Abdulwhab et al. (2010) presented a reliability-centered approach to diminish the excessive risk associated with the downtime of generating units under all load conditions, thus increasing the asset's reliability. They first divided the system into functional zones to target the main issues and simplify the entire model. Then, with the help of both deterministic and probabilistic techniques, a Wellbeing analysis was introduced based on three indices: the first is the probability of a healthy state, second is the probability of a marginal state, and last is the probability of a risky state. Finally, the results were that with the maintenance optimization using wellbeing analysis, the assets tend to be more reliable.

Another attractive reliability centered maintenance document is Rivera Torres's article(2018). The main objective is to avert failures, enhance uptime, and increase work life. Through probabilistic Boolean network modeling, one can anticipate the future behavior of the assets feeding the entire system using bio-inspired tools. Moreover, it can predict prognostic performances to improve the whole system's reliability by implementing a better preventive maintenance plan.

2.4 Literature Review Summary

In summary, there exist many articles that provide strategies to help improve preventive maintenance policy. Several studies provided cases on operating machines, studied the uptime and downtime of the asset, and implemented either a risk-based or reliability-centered maintenance strategy to achieve an optimal maintenance strategy and lower failure cost to a minimum. Other articles focused on non-operating construction structures, analyzed their lifetime, defects, and failures, and applied a risk-based maintenance strategy to help find an optimal preventive maintenance policy with low failure consistency and minimized cost. Table 4 demonstrates an overall summary list of maintenance optimization articles with an emphasis on what elements in each article inform this current thesis.

Table 3: represents a summary of the LR section and critical elements in each study.

Name of the article and Reference	Summary	Vital Elements for Methodology
Assessment of Waterproofing Failures in Concrete Buildings and Structures(Mydin et al., 2017).	Focused on listing waterproofing failure types, elaborating on their effect on the concrete structure, and providing remedial solutions for structural buildings.	-Water intrusion failures. -Importance of waterproofing in both non-public and public buildings.
Different types of Waterproofing(Constro Facilitator, 2020).	This report represents a general outline of the different types and components of waterproofing.	Waterproofing components.
Long-term performance of EPDM geomembrane in el Boquerón reservoir(Noval et al., 2014).	This study focused on the EPDM sheet-based waterproofing system and carefully studied its durability for 21 consecutive years under constant humidity. This study shows that ultraviolet radiation and weather reports are leading root causes of waterproofing deterioration.	The primary root causes of waterproofing failures are the weather reports, mainly ultraviolet radiation.
A Field Study of the Performance of EPDM Roofing at Air Force Facilities(Rossiter et al., 1991).	This study provided technical inspection on the EPDM waterproofing roofing maintenance system at several military air force bases with low-sloped roofing systems to inspect the condition and quality of the EPDM structure and the applied routine preventive maintenance.	-Condition rating reports are useful to classify categories in an inspection. -Need for preventive maintenance for waterproofing systems -Types of failures in the EPDM structure. -Abuse and human error are major root causes that influence EPDM failures.
Preventive Maintenance at General Aviation Airports Volume 2: Guidebook(Ploeger et al., 2015).	Proactive maintenance in public buildings is obligatory, especially in airports. Like any other public figure, the airport	There is a need for a proper proactive maintenance plan to meet the requirements set by the client, especially at airports and public facilities.

	should meet several requirements as put by the client to retain the perfect image set by the country.	
A risk-based modeling approach to maintenance optimization of railway rolling stock: A case study of pantograph system(Dinmohammadi, 2019).	Provided a prolonged step by step risk-based model to improve the preventive maintenance inspection durations and decrease risks associated with failures.	-A risk-based optimization strategy works well on machines and heavy equipment. -A step by step methodology is a simple but effective procedure to follow to tackle failures. -Dissecting the entire asset into several parts and analyze each part on its own has proven efficient in the study.
A risk-based model for inspection and maintenance of the cross-country petroleum pipeline(Dey, 2001).	Through risk assessment of pipeline stretches, the researcher examined the losses incurred with the excessive inspection time needed to find the leakage problems of pipelines and thus resulting in a high maintenance cost.	-Risk assessment reduces inspection costs. -AHP model efficiently categorizes all root causes, giving a detailed review of the main reasons for failures' existence. -Dividing a massive pipeline into several stretches studying each area on its own. -A risk-based optimization strategy works well on structural assets.
Probabilistic lifetime-oriented multiobjective optimization of bridge maintenance: Combination of maintenance types(Neves et al., 2006).	The article aims to reach the best combination of conditions, safety, and cost. This is achieved through satisfying all performance constraints of deteriorating bridges' silane during a specified time horizon, under multi-objective maintenance, and then compared to a single-objective maintenance strategy.	-Multi-objective solves several objective criteria through an efficient preventive maintenance strategy. -Implementing a multi-objective risk-based strategy has a significant impact on both money and time reduction.
Risk-Based Maintenance Optimization of Aging Highway Bridge Decks(Lounis, 2015).	The focus was to improve the condition of the bridge decks while reducing the maintenance and user costs. Doing so minimizes both the probability and consequences of the projected property failures.	-Importance of condition rating order, which helps assess the risk of failure. -The multi-objective strategy tends to be a highly efficient tool to diminish failure costs.
Modeling preventive maintenance of	The research presented a reliability-centered	Asset reliability is vital to reduce the risk associated with

manufacturing processes with probabilistic Boolean networks with interventions(Rivera Torres et al., 2018).	approach to diminish the excessive risk associated with the downtime of generating units under all load conditions, thus increasing the asset's reliability.	failure and downtime by providing a prognostic strategy that increases the uptime of such assets.
Maintenance Scheduling Optimization Using a Genetic Algorithm (GA) with a Probabilistic Fitness Function Maintenance Scheduling Optimization Using a Genetic Algorithm (GA) with a Probabilistic(Abdulwhab et al., 2010).	The main objective is to avert failures, enhance uptime, and increase work life. Through probabilistic Boolean network modeling, one can anticipate the future behavior of the assets feeding the entire system using bio-inspired tools.	Analyzing prognostic behaviors of machines to improve the reliability and uptime.

2.5 Conclusion

Both RCM and RBM strategies provide solutions in the maintenance field, and expertise to help solve problems associated with failures in many facilities. However, based on previous articles, RBM works better with structural assets, such as waterproofing, than RCM. RBM focuses on the failure risks of such an asset, which has a great effect on the entire facility's durability, rather than focusing on the downtime of such assets considering that associated costs to downtime are immensely lower than that of the risk of failure. Considering that waterproofing is a structural asset, a risk-based maintenance strategy is considered as a better option. In this work, we seek to specify a risk-based maintenance strategy by using machine learning techniques to derive the probability of failure for EPDM sheeting at an airport. Machine learning techniques allow us to incorporate weather conditions in addition to time to failure as a predictor of the probability of failure. These failure probabilities combine through simulation with the probability of repair upon inspection to permit a multi-objective assessment of the risk-based cost implications of preventive maintenance policies against waterproofing failures and the consequences of such failures in heavily used public facilities such as airports. A step by step methodology will help decipher the entire problem and dissect it into areas of study and analysis to help achieve the optimal preventive maintenance strategy with a minimized total maintenance cost.

Chapter 3

Methodology

Despite the importance of waterproofing at airports, managers find it hard to predict leakage and to suppress all of its failures (Inazumi et al., 2017). Moreover, waterproofing failures' consequences are malignant and highly unplanned. When it comes to the tasks to repress leakage, maintenance crews depend mostly on experience to inspect and find the problems, which is considered to be a particularly burdensome maintenance process (Dey, 2001). Consequently, managers would prefer to follow a reactive/corrective maintenance approach rather than implementing an efficient preventive maintenance plan. For most assets, a reactive/corrective strategy is generally more costly. Waterproofing requires dedicated and highly professional technicians, significant maintenance costs, and proper maintenance planning tools to preserve its quality and functionality. The research cited here showed that applying risk-based management techniques in this domain could contribute to optimizing and carrying out the best preventive maintenance plan. Eventually, this process would help reduce the unexpected leakage failures and subsequent risk costs, high inspection time expenses, and unplanned maintenance issues, based on the given margin of resources (Inazumi et al., 2017).

To develop a risk-based management strategy for the maintenance of waterproofing at airports, this thesis follows a three-step strategy. First, a quantitative risk-based modeling process is applied to airport waterproofing in order to understand the root causes of failure and the impact of such failures. Second, based on the probabilities of failure and the consequences of failure, a total risk model is derived to quantify the risk and structure of waterproofing risk-interactions, which will become the basis of a simulation designed to identify the most promising maintenance strategy. Third, the simulation itself serves to support the analysis of several preventive maintenance strategies dedicated to reaching an optimal multi-objective risk-based maintenance strategy. Figure 10 shows the flow chart of all the methodology steps.

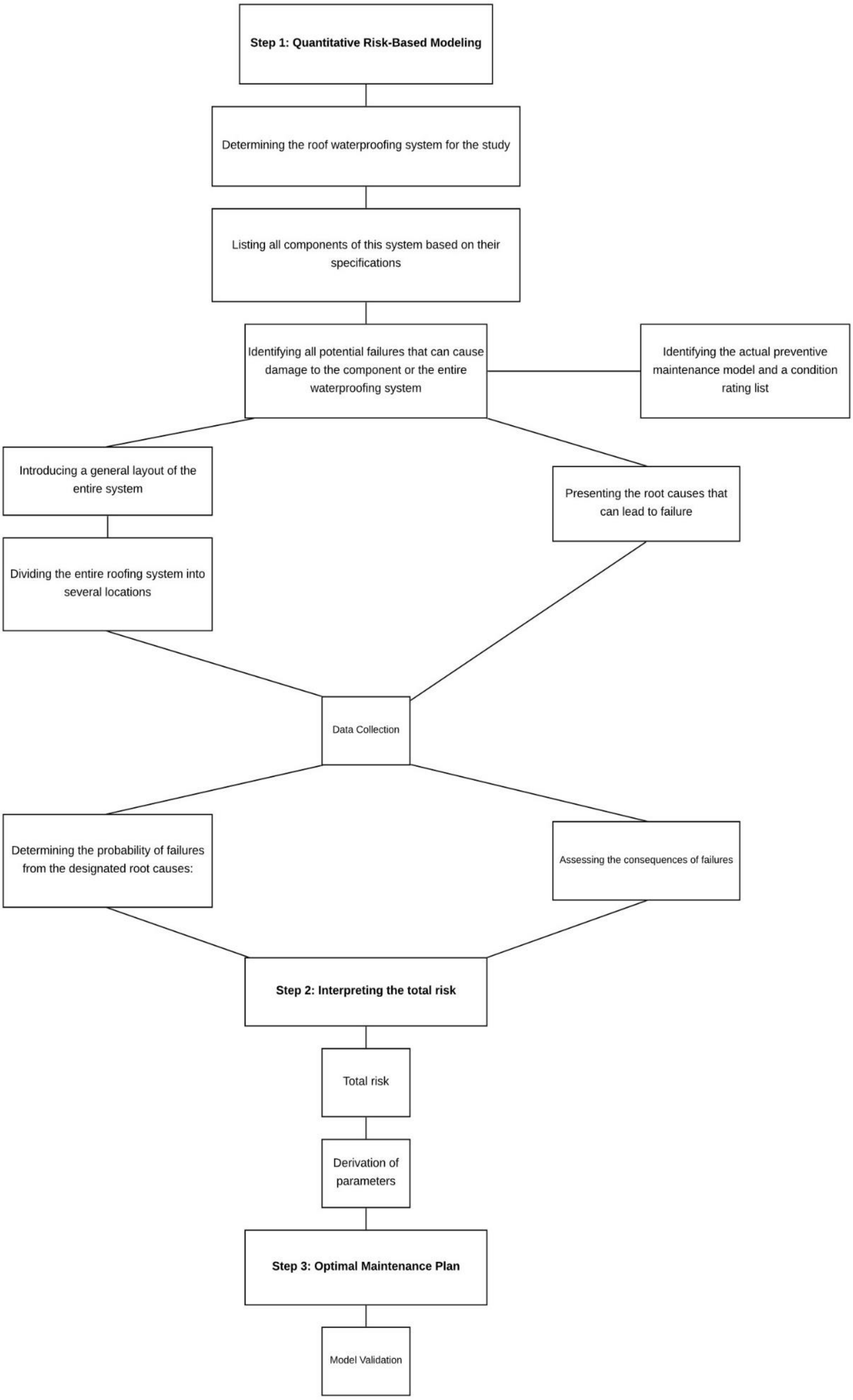


Figure 10: Methodology Flow Chart.

3.1 Step 1: Quantitative Risk-Based Modeling

In this section, an outline of the quantitative risk-based modeling methodology for maintenance planning and optimization is presented relative to roof waterproofing at airports. This process serves to define the entire system at hand, dissect it into distinct criteria based on components and locations, study previous failure data and probabilities based on the root causes, and analyze the consequences of such failures. Chapter 4 will show, in detail, these general steps applied to a case-study airport. The nine steps are as follows:

3.1.1 Determining the roof waterproofing system for the study

This first step is to describe the waterproofing system itself. Generally, waterproofing is essential to hinder water leakage, which would repress the use of water buckets to contain the dropped water under penetrated areas. This necessary reinforcement has many types and components. Nevertheless, choosing a feasible system depends on the goals and objectives of the entire organization. This said, each type is profiled by its elements, for example, the self-adhesive EPDM (ethylene propylene diene monomer rubber) is considered cheap, compared to torch-based EPDM system, but requires high implementation and maintenance follow-up. As a first step, a general idea of the asset is established.

3.1.2 Listing all components of this system based on their specifications

After identifying the main asset at hand, it is essential to dissect and go deeper into that waterproofing system. As mentioned in the literature review, each type of waterproofing is beneficial and useful based on its functionality. So, after showing the system's overall quality and specifications, a part of building a risk-based maintenance strategy is to identify and present each component's structure, function, materials, method of application, and recommended place of use based on the recommended supplier's detailed product description. The structure defines the component's features, chemical composition, and design. It portrays a general understanding of the component. As for the function, it defines the component's adaptability to the applied surface and to impede water and humidity intrusions. Then, the method of application portrays the steps needed for applying the component as per the recommended supplier's method statement. As for the recommended area of use, it shows the compatible environments recommended for each component. Finally, both the materials and staff provide a general idea of materials and workforce required for each component during application. Listing all components is one of the significant steps in the report. As previously used by Dinmohamadi’s railway report(2019), this step would help differentiate one area from the other, thus simplifying the entire airport facility’s waterproofing asset into different sectors with distinct specs.

Table 4: represents a general prototype overview of each component’s design and specs.

Components	**Structure**	**Method of Application**	**Recommended Area for Use**	**Materials**	**Maintenance Required Staff**
Component 1					
Component *n*					

3.1.3 Identifying all potential failures that can cause damage to the component or the entire waterproofing system

After analyzing all components, this step requires systematically working through each component and identifying all the ways it might fail. Each component has its own design, failure types and intensity, and effect on the serviceability of the entire system. Waterproofing defects are the phenomena that show the condition of the waterproofing asset. Such defects can be signs of deterioration (crazing, cracking, discoloration, or extreme abrasion) and reduced flexibility of the rubber material judged by pulling, pushing, or bending. Each component would then be subject to detailed analysis and study based on previous experience, defect types, and areas of defected assets to assess the condition of the defected asset. This study would then be

Figure 11: Low intensity-leakage.

Figure 12:Moderate-intensity leakage

Figure 13: High-intensity leakage.

directly related to the severity of having such defects; some would be of small importance; others might end up dealing with excessive failures and consequences. Figures 11, 12, and 13 represent the different intensity of failures resulted from waterproofing.

3.1.3.1 Identifying the actual preventive maintenance model and a condition rating list:

As in Lounis's et al. article(2015), a condition rating order will be provided on each component based on its specs and associated potential failure consequences and intensity. A more detailed condition rating tends to provide precision and technical planning during preventive maintenance. Table 6 represents a demonstration of the rating and basis of the waterproofing condition. Each rate provided is supported by visual technical inspection based on potential failures associated with each rating. For example, an excellent rating would suggest that the system is functioning correctly, while a poor condition suggests that high-intensity potential failures might appear, if not acted upon. This condition rating system is influenced by the maintenance policy presented. A detailed preventive maintenance policy based on detailed potential failures might end up having a 10-rating module. While a less sophisticated policy might end up having up to just a 3-rating module.

Table 5: A condition order rating module for preventive maintenance.

Rating	Basis
5	Excellent condition.
4	Good condition.
3	Fair condition.
2	Bad condition.
1	Poor condition.

3.1.4 Introducing a general layout of the entire system

Presenting a layout of the entire system tends to provide a detailed structural representation of the entire system, which helps tackle the failure problems from an innovative engineering perspective. This layout would represent all the components’ locations and areas. Figure 14 represents the layout of a typical airport. As shown in the Figure, the airport can be divided to separate sectors. The public area highlighted in light green, which can be named as the terminal sector, is a public space open to all. The checkpoint and sterile areas highlighted in red and orange are commuter and staff only sectors. Finally, the apron and runway areas that provide the airplanes’ parking spaces, and takeoff and landing spaces, respectively. The base of the study will be the entire concrete base waterproofing roofing systems, basically at the public checkpoint and sterile areas.

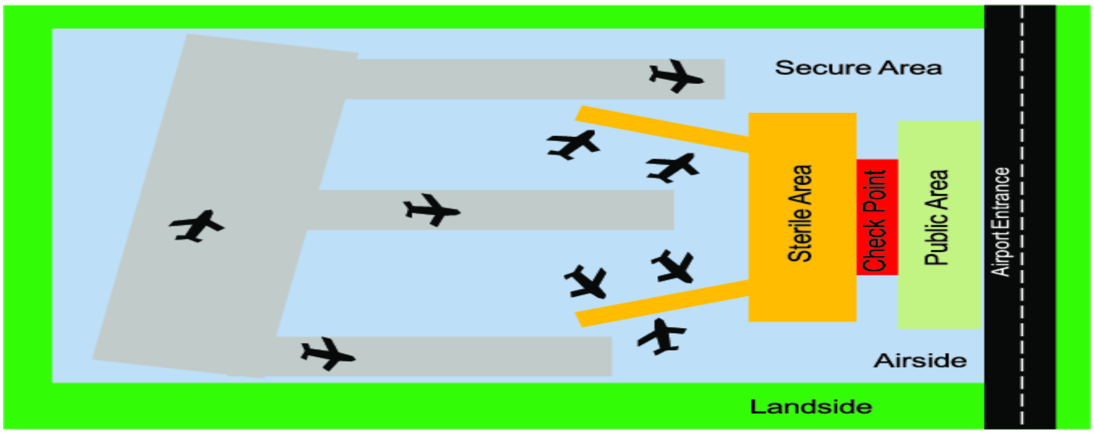


Figure 14: An airport general layout.

3.1.5 Dividing the entire roofing system into several locations

Public facilities can be challenging to analyze due to their massive areas. Airports around the world have a total area ranging between 1630 square meters up to a whopping 36.75 square kilometers(Julie, 2017; RedShed, 2018). Given that and in compliance with Dey’s pipeline article(2001), it is efficient to divide the total area into several study locations. Assessing vast areas at once can be a hectic procedure to analyze failures and implement a maintenance strategy covering the entire space. Nevertheless, approaching the system as a case by case categorized study provides efficient and straightforward optimization planning to each location separately. Locations can be divided according to root causes, consequences, components, and several other key determinants.

3.1.6 Presenting the root causes that can lead to failure

This step introduces the stimuli that explain the failures designated to each location and component of the entire system. Many analytical approaches can help in identifying the root of dysfunctions, like Root Cause Analysis (RCA) and Failure Tree Analysis. Indeed, it is vital to ask the why question (5 w's), as much as required, to reach the core of all problems. Furthermore, as mentioned earlier, root causes can be divided into several types. Some of them are structural damages, functional failures, degradation, human errors, and abuse, and natural (external) hazards. Unfortunately, airports are exposed to several external haphazard stochastic problems, which might restrict an efficient maintenance plan. Such examples might suggest deficiencies and ducting penetration. As in Dey's article (2001), an AHP model would fully translate the root causes in order of importance. Figure 15 is a sample of the AHP model that represents all waterproofing root causes. As presented in the model, the root causes can be divided into factors and sub-factors depending on the total effect on the probability of failure of the asset. Based on historical data mining and collection, the system can provide probabilities of failures associated with each root cause acting as a determinant (Romanowski & Nagi, 2001).

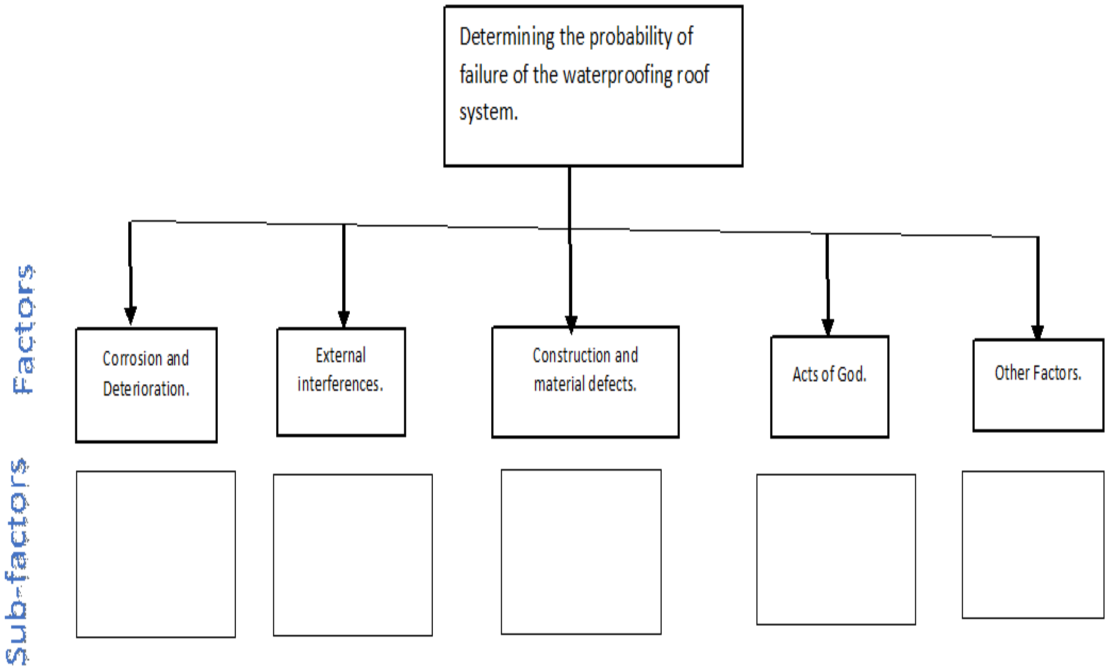


Figure 15: AHP analytical Hierarchy Process Model.

3.1.7 Data Collection

After recognizing and defining the whole system, dividing the entire area into separate locations of study, and analyzing both the potential failures and root causes of each component, historical data can be collected and divided as per the specified criteria. Each criterion is differentiated depending on both the location and component.

3.1.8 Determining the probability of failures from the designated root causes

Now that we know all the potential failures designated to all their root causes, we must evaluate the sporadic interval between such failures associated with the defects. From previously attained data collection, and with the help of machine learning techniques, we can determine the probabilities. These values will then give the facility manager a general idea of the possibility of having failures for the components across the identified locations.

3.1.9 Assessing the consequences of failures

Consequently, the outcome of a waterproofing failure is leakage. However, failure consequences can be classified by location and intensity. In other words, leakage in private offices has less impact on the serviceability and safety of the airport than intensified leakage on electrical and mechanical machines or in public areas. Thus, it is essential to classify failures along multiple dimensions of impact.

3.2 Step 2: Interpreting the total risk

This step provides an analytical approach to study the entire risk associated with the applied preventive maintenance strategy and failures resulting from it. This depends directly on the data covered in Step 1.

3.2.1 Total risk

Once the system has been thoroughly dissected, an assessment of cumulative risk can be undertaken by modeling the influence of each component at each location on the entire system. To compute the total risk of the entire system (R_T), several elements are analyzed relative to a designated preventive maintenance policy. The risk function is as follows(Khalifa, Khan, & Thorp, 2015):

$$\Rightarrow R_T = \sum_{Nu} (C_{Repl} + C_O t + C_{PM}) + R_f - \sum N_u R_v$$

1) C_{Repl} is the cost of replacing the asset after its serving life.
2) C_O is the cost needed to keep the asset operational in a certain period(t).

3) C_{PM} is the cost of the preventive maintenance task.
4) R_f is the risk of failure, which is the cost of the failure (C_f) multiplied by the probability (P_f) of it happening all over again.
5) T is the maintenance policy’s scheduled duration for preventive maintenance.
6) t is a certain period of the study.
7) $R_{(v)}$ is the component remaining value after the time(t).
8) N_u is the number of components under study.

Now, to analyze the risk of failure and to compare different approaches to the system through using different maintenance strategies, the risk of failure $R_{(T)}$ at a specific time under maintenance policy intervals (T) for a single asset is as follows:

$$R_T = C_{Repl} - R_v + C_O * t + C_{PM} * t/T + P_f * C_f$$

$$= C_{Repl} - (C_{Repl} - C_{Repl} * t/\text{useful life}) + C_O * t + C_{Repair} * t/T + P_f * C_f$$

$$\Rightarrow R_T = C_{Repl} * t/\text{useful life} + C_O * t + C_{PM} * t/T + P_f * C_f$$

3.2.2 Derivation of parameters

This part is an explicit explanation of all elements of the risk function. In order to compute the entire risk, each element of the formula should be studied on its own. Keeping in mind that the entire formula depends heavily on the asset studied and the maintenance policy set by the manager of the facility, which in this case is the study of the waterproofing roofing system and its preventive maintenance schedule at airports. As mentioned before, the airport sample provided is divided into the main Locations of study: 1,2,3,4, etc. Each location has its designated specifications, probability of failure, root causes, size, and set of waterproofing components. As a start, the cost of replacement (C_{Repl}) is the expense associated with replacing the asset by a new one when it exceeds its useful life of the entire location. Usually, for waterproofing components, useful life is around 25 years, and the cost of replacement depends on the material, implementation, and labor cost. Next is the operating cost (C_O); this is the cost that keeps the system running. For example, oil change for generators is a part of the expense associated with operating. However, when it comes to waterproofing, its value tends to become negligible compared to others. As for the preventive maintenance cost (C_{PM}), it is the cost that helps the asset avoid failures within its lifetime duration. This depends mainly on the maintenance effort provided by the preventive maintenance policy. Preventive maintenance is divided into two categories: inspection and repair. In order to have a repair event, inspection should be made on the asset. However, it is not necessary to repair on each inspection mode; some areas would reveal excellent condition during that time. Thus, the cost of an inspection is fixed and necessary for the preventive maintenance model; on the other hand, the cost of repair is directly related to the frequency based on historical data and experience. Lastly is the failure cost; this includes all costs associated when a certain asset fails or breaks down. This element is divided into two categories: the cost of replacement/repair and the consequences' cost.

3.3 Step 3: Identify the Optimal Maintenance Plan via Simulation.

Once a complete understanding of failures, their risks, and their consequences, has been established, we use simulation to test the efficacy of multiple potential maintenance strategies. Relying on simulation, we will develop a framework to test multiple maintenance policies. Based on the resulting total risk indicated by the simulation, a minimal risk preventative maintenance strategy can be selected. The parameters of the total risk formula derived in Step 2 are at the heart of the simulation. Table 7 represents a prototype of preventative maintenance (PM) policy. Each task represents a specific work order that adds to the system's overall reliability in terms of the asset's likely failure in the future. The maintenance staff would do this at specific time intervals (*T*) based on the management policy. The PM policy can be studied on separate categories based on location and component, and each category can have separate tasks and time intervals. Tasks are directly related to the durability and specifications of the waterproofing system's components. The time intervals tested should be related to the root causes and potential failures of each component in each Location.

Table 6: PM Policy Model

SN	Task Description	Time Interval(T)	System Reliability Function
1			
2			
3			

3.3.1 Model Validation

While validation of the results in practice will be difficult, we will study the validity of the model in two ways-- through scenario analyses (by changing parameters to model extreme cases and determine if the results are logical) by using R Studio as a simulation and statistical analysis application, and through expert opinion.

Chapter 4

A Case Study: Application to a prototype airport

In this section, the outlined methodology for the development of a risk-minimizing maintenance strategy is implemented on an EPDM waterproofing system at a prototype airport with synthesized historical data. This airport consists of the main airport facility, three runways, and several other supporting facilities and organizations. The location under study is the main facility, which can be named as the terminal building.

The terminal building is a 6-floor facility that has an approximate total area of 65,400 sqm. Its roof is a reinforced concrete base slab topped by a finishing screed to maintain a low-sloped profile for drainage. Concrete parapets provide structural barriers around its perimeter as extensions of the wall on the roof. This prototype public building's roof consists of two distinct areas of study: the open locations, where the roof is exposed to external climate conditions, and the closed ones, which are mechanical rooms shielded by a steel-based structure to avoid external climate exposure. The mechanical rooms consist of heavy machinery that feeds the HVAC system of the entire airport. This prototype facility has an EPDM waterproofing system on the entire roof. The choice of EPDM for this study stems from its durability but the potential to suffer failure for a mix of intrinsic and extrinsic reasons.

4.1 Step 1: Quantitative Risk-Based Modeling

4.1.1 Sure-Seal EPDM waterproofing system

The waterproofing system of this thesis is the EPDM rubberized system. As mentioned before, EPDM stands for ethylene propylene diene monomer, which is the combination of a carbon-based structure to form a rubberized sheet. It specializes with high flexibility and durability, as it can withstand a tensile pressure of 25MPA, and can elongate up to more than 300 percent of its actual size. This type of system has proved to be highly effective in providing a solid shield from humidity and water intrusion. Since the 1960s, this system has been one of the most used reliable products against water penetration (Roofing Contractor, 2016). Over 13 billion Sure-Seal EPDM roofs were installed, and over 45 years of proven performance (Carlisle Syntec Systems, 2015). This system has shown excellent results with low-sloped and several roofing decks' designs and properties. There are two methods of EPDM sheet-based applications, the first is through an adhesive, and the other is through the torch. The adhesive-based method is cheaper and easier to maintain and apply than that of the torch-based implementation; however, defects are more often observed on the first type of application. So, the adhesive helps stick the rubberized sheet to one another and firmly bond them to the concrete base through an adhesive bonding agent. While the torch-based uses exclusive welding tools to melt the rubberized structure of the EPDM sheets on the concrete base to firmly stick them together and result in a rigid surface to protect from water intrusion, we assume that the prototype airport uses the adhesive-based system because of its comparatively lower cost along with the easier and cheaper maintenance associated with it.

4.1.2 Listing all components of this system based on their specifications

This type of waterproofing agent can be separated into two categories: the base sheet and the skirting. The base sheet is covered with heat insulation boards and ballast for protection and applied over the entire concrete slab. As for the skirting, it is the vertically installed EPDM sheet for a height of 20 centimeters on upstands and perimeter parapets, which then overlaps the existing base sheet. Figure 16

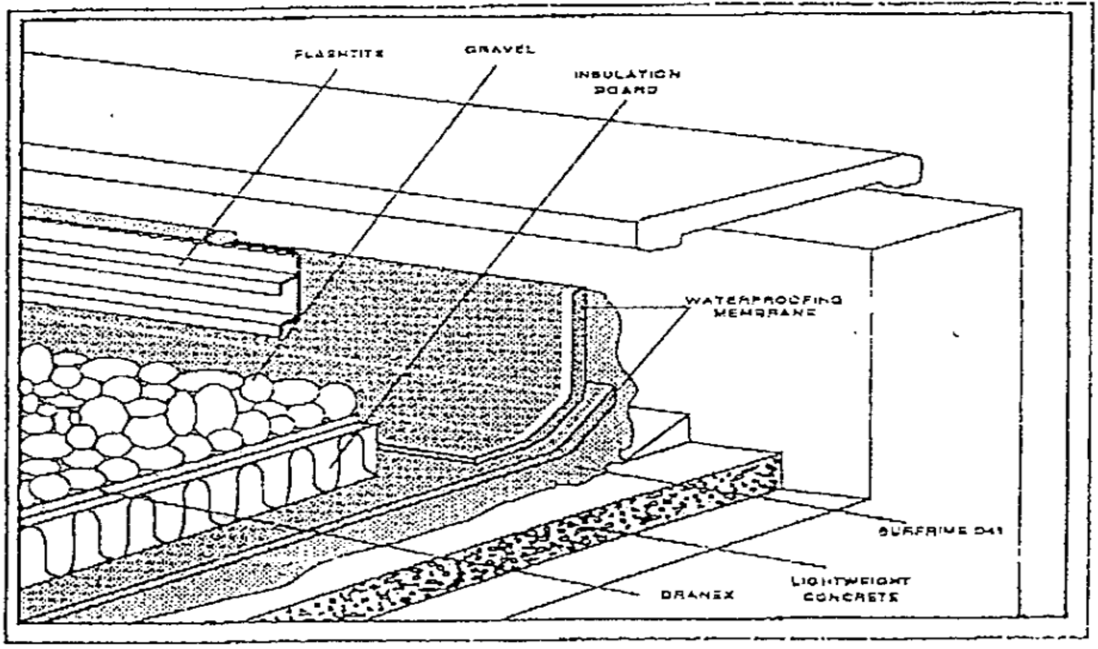


Figure 16: A sketch of the EPDM structure that consists of base sheet and vertical skirting.

demonstrates a sketch of the EPDM structure. The waterproofing assets in this case study are then divided into three different components: sheet-based, liquid-based, and cementitious. As shown in Table 8, each component has its specification and functionality.

Table 7: Components' specifications and functionality.

Components	Tremco Liquid Waterproofing Membrane TREMproof 201/60 (Liquid-Based)	Carlisle Sure-Seal EPDM Waterproofing Membrane (Adhesive Sheet-Based)	Thoroseal FX 110(Cementitious Material)
Structure	TREMproof 201/60 is a modified polyurethane waterproofing membrane. It has a particularly dense texture that immediately bonds to the concrete surface.	The EPDM waterproofing membrane is a carbon-based rubberized sheet. It provides a sturdy and durable shield that prevents water from intrusion. Heat insulation boards then protect the sheets and ballast from weather and climate exposure, and abuse, respectively	This material has a well-known sturdy cementitious structure. It is a composition of liquid and cement compounds.
Recommended Areas for Use	Internal and exposed locations (mainly for tight areas where sheets are hardly spread.)	Exposed locations.	Internal and unexposed locations.
Maintenance Required Staff	Waterproofing technicians.	Waterproofing technicians and laborers.	Waterproofing technicians.

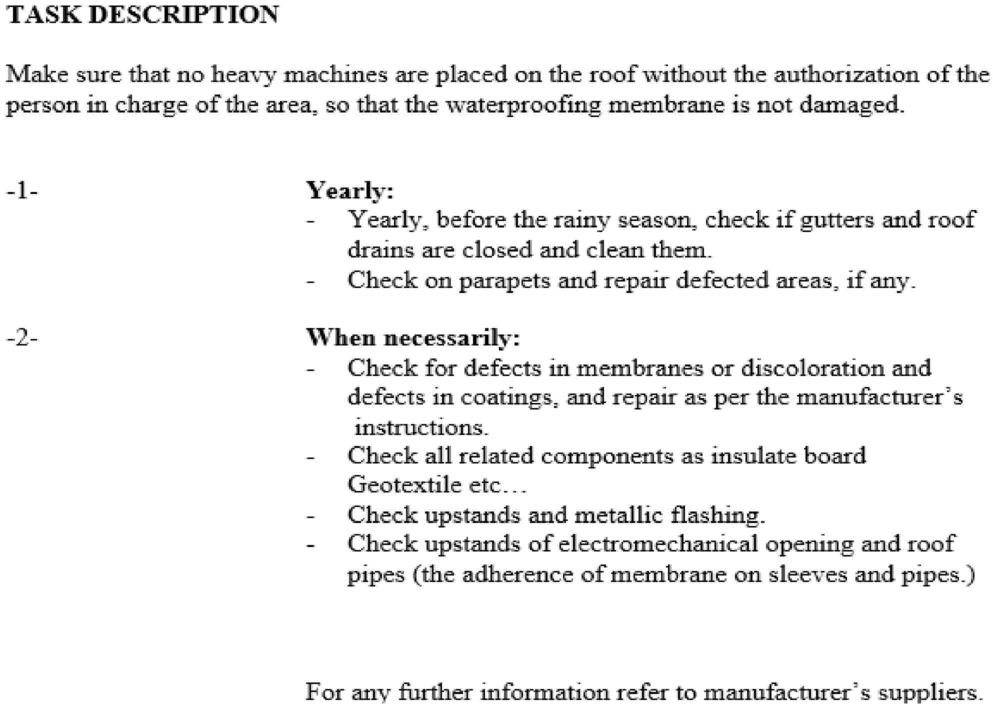
Materials and Equipment	TREMproof waterproofing barrel, mixing machine, roller, and trowel.	EPDM sheets, adhesive, silicon, and Flashtite aluminum strips for flashing.	Thoroseal (A and B), mixing machine, trowel, and Thoroseal FX mesh.
Method of Application	The TREMproof 201/60 is a sensitive product to handle. After maintaining a clean concrete surface, this dense product is then applied through a roller. Avoid blisters, peeling off, and cracks through proper application.	After maintaining a clean concrete surface, the adhesive is applied on both the concrete or screed surface and the existing sheet’s splicing area for overlap. Then, with extreme caution, spread the sheet over the area. Skirtings are applied using the same methods to bond with the concrete base and upstands. Aluminum flashing and silicon protection are then applied on parapets and upstands for vertical skirting protection.	Compounds A and B are mixed, as per manufacturer’s recommendations. Then, after thoroughly cleaning the concrete structure, two coats are applied using a trowel. It is recommended to place an FX mesh between the coats as reinforcement to avoid shrinkage and cracks.

4.1.3 Identifying all potential failures that can cause damage to the component or the entire waterproofing system

Each of the provided components has its own set of potential failures as a result of different types of causes. The sheet-based system is the sturdiest of all components; however, certain defects might appear on the EPDM through time. Most common defects are deterioration (crazing, cracking, discoloration, or extreme abrasion), peeling off, and reduced flexibility of the rubber material judged by pulling, pushing, or bending. As for the liquid and cementitious components, signs of shrinkage, cracks, and peeling off are the most common types of defects appearing on those components.

4.1.3.1 Identifying the existing preventive maintenance model and a condition rating list:

Like any other asset, waterproofing deteriorates with time. It is up to the facility's management to implement a preventive maintenance strategy to help maintain the asset through its useful life. Figure 17 shows the preventive maintenance model currently applied in the case study facility. This preventive maintenance model begins with introducing the first leading root cause for failure -- human abuse and error. While no clear mechanism to prevent such abuse is stated, it is noted that such abuse should be avoided.



TASK DESCRIPTION

Make sure that no heavy machines are placed on the roof without the authorization of the person in charge of the area, so that the waterproofing membrane is not damaged.

-1- **Yearly:**
- Yearly, before the rainy season, check if gutters and roof drains are closed and clean them.
- Check on parapets and repair defected areas, if any.

-2- **When necessarily:**
- Check for defects in membranes or discoloration and defects in coatings, and repair as per the manufacturer's instructions.
- Check all related components as insulate board Geotextile etc…
- Check upstands and metallic flashing.
- Check upstands of electromechanical opening and roof pipes (the adherence of membrane on sleeves and pipes.)

For any further information refer to manufacturer's suppliers.

Figure 17: Preventive Maintenance Index.

Then specific tasks are stated to address other potential causes of failure. Specifically, annually roof drainpipes and gutters should be cleaned and checked before the winter season. Furthermore, all concrete parapets are to be checked and repaired if there are any defected areas. Indeed, this scheduled preventive maintenance activity of drainpipe cleaning and concrete repair are significant tasks to avoid water from penetration, but both have nothing to do with the waterproofing asset.

The second task, however, is more directly related to waterproofing, where, when necessary, the EPDM sheets are thoroughly checked for discoloration and defects, and insulation boards, cement tiles, upstands, and metallic flashing are inspected for any problem. Finally, upstands and roof openings are checked and made sure that there are no holes or spaces where water could run through and leak. These activities are closer to an actual waterproofing maintenance policy but divert from a proper preventive maintenance task schedule. The "when necessary" term is an unclear term to use in maintenance; it suggests that when failures tend to appear, and the situation necessitates for corrective maintenance, only then maintenance staff will fix the waterproofing elements as suggested by the preventive maintenance mode.

Table 8: Actual condition ratings.

Rating	Basis
1	Excellent condition, no failures were found; the system works properly, etc.
2	Poor condition. Substantial failures, water leakage, defected waterproofing, damaged skirting and flashing, signs of corrosion, and steel bars' exposure, etc.

In all, this preventive maintenance model can be classified as a corrective or run to fail type of policy, rather than a reliable preventive/proactive strategy.

In support of this maintenance plan, the facility managers assess the condition of the waterproofing based on a diminished two-scale level scale system, as described in Table 9. The first rating gives a general idea that the system is working well without any failures, and the following conditions show the need for a corrective maintenance work order to stop the failure and its associated consequences.

4.1.4 Introducing a general layout of the system

Even after dissecting the whole system into components, it retains a complex structure, due to its relatively large area, which can make the job of maintenance staff difficult in terms of organizing routing and maintenance task scheduling. As in Dey's(2001) pipeline article, a great technique to simplify the model, even more, is to divide the entire asset into different locations with distinct properties. In general, the main terminal building of this case study can be divided into sub-categories, where each would have a different property profile. The first order classification would be dividing the total area into two: the sterile and the public, as shown in Figure 18. The public section holds receiving halls, visitor areas, and ticket lobbies, etc. While the Sterile sector holds the duty-free area, departure and arrival gates, holding rooms, and checkpoints.

4.1.5 Dividing the entire roofing system into several locations

Each sector has its properties, components, failure modes, consequences, and root causes of those failures. The next step is to differentiate the entire roof into exposed spaces and closed mechanical rooms in order to relate each divided space to its designated components of the study. Figure 19 demonstrates an overview of the 2nd order Location breakdown scheme. The blue-hatched areas are mechanical rooms. The management prefers the application of cementitious components in closed roof

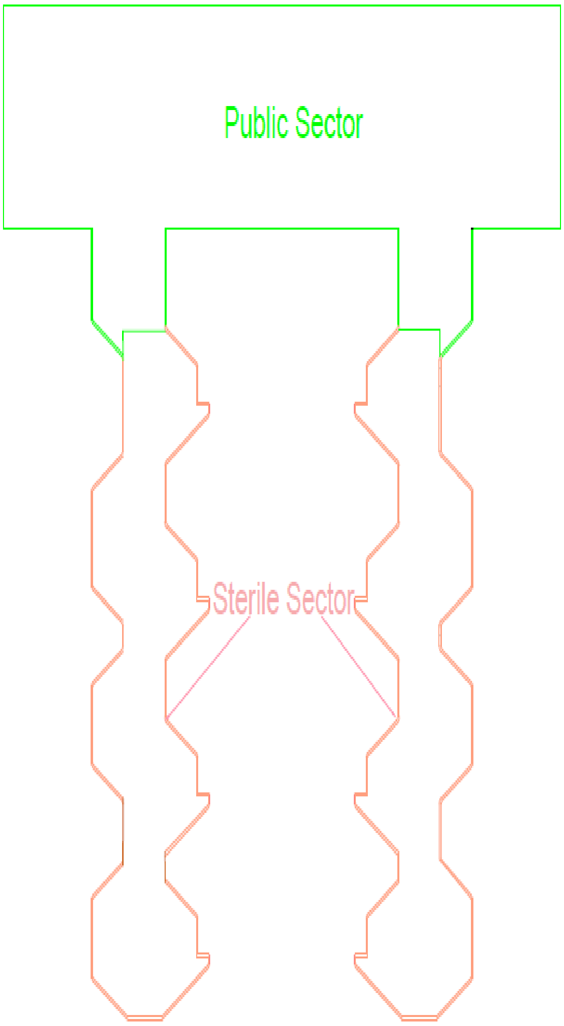


Figure 18: 1st order classification layout as per public and sterile sectors.

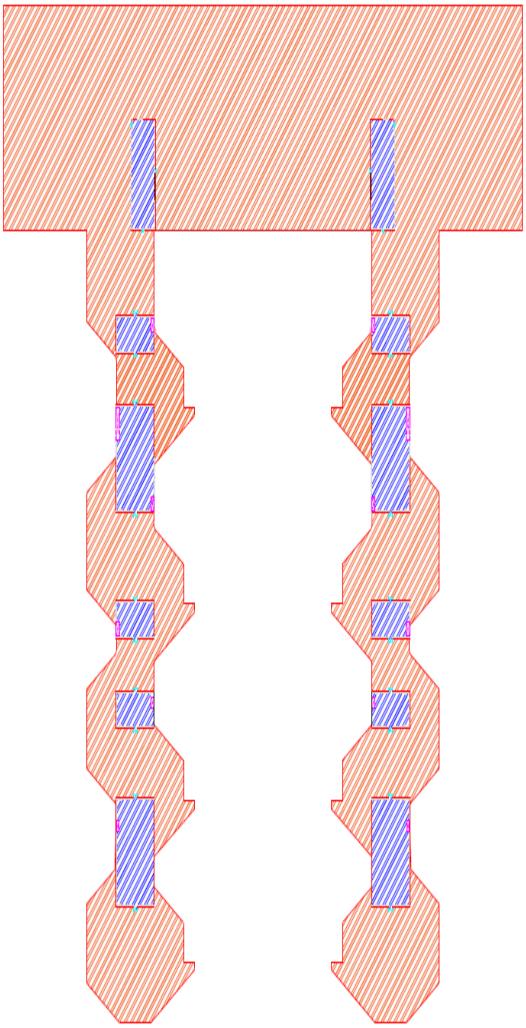


Figure 19: 2nd order classification as per components, consequences, and exposed and closed areas.

surfaces as such. While in the exposed areas, both the liquid and sheet-based EPDM waterproofing are applied.

Finally, as a 3rd order classification, the layout will combine both previous models into a simplified four location study. Figure 20 shows the 4 Locations used for data analysis. Locations 1 and 2 are the exposed roofs above the public area; they are both the same sizes and consist mostly of EPDM sheets as waterproofing. These Locations are both the same size and consist mostly of EPDM sheets as waterproofing. However, climate differences (sun exposure, wind direction, etc.) from one area to the other affect the probability of EPDM sheet failure so that each location will be studied on its own. Location 3 represents the exposed roof above the sterile area. Although it consists of the same component, failure consequences in this area differ from that of Locations 1 and 2, thus making it a third Location to be studied on its own. Lastly, Location 4 represents the closed roof surfaces, where the

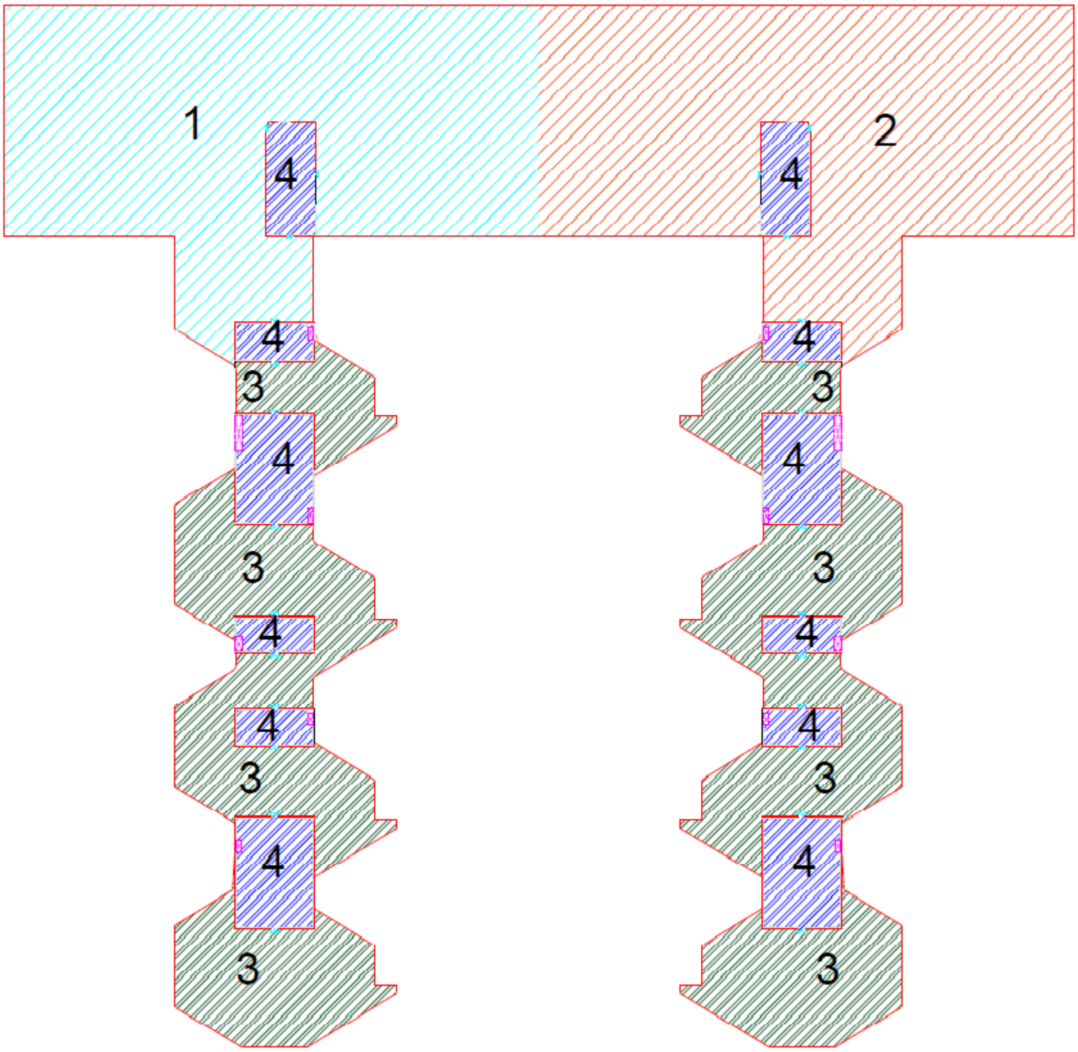


Figure 20: 3rd order classification of the 4 locations as per component type, climate change, closed and exposed

roofing component used is the cementitious Thoroseal FX 110. It is thus designated as a location of study on its own. Now that the system is dissected into distinct and straightforward categories, historical data, root causes, and failure analysis are then implemented on each category of the model. Each location's risk would then be studied, and a simulation is run on each location to identify preventative maintenance policies that minimize the risk of the entire system. Table 10 is a list of the locations with their sizes and components.

Table 9: is a list of Locations, sizes, and components.

Locations	Size(sqm)	Type of component
1	17,810	Sheet and liquid-based
2	17,810	Sheet and liquid-based
3	21,300	Sheet and liquid-based
4	8,520	Cementitious

4.1.6 Presenting the root causes that can lead to failure

Although the EPDM waterproofing system can maintain a durable shield from water penetration that can last for more than 30 years, many stimuli exist to increase the probability of having several defects during the system's lifetime. Each previously explained component of the EPDM waterproofing system is under significant failure influencers that affect the durability of the whole system. Figures 21, 22, and 23 demonstrate the AHP model of the sheet-based, liquid-based, and cementitious components, respectively. Both the sheet-based and liquid-based components have the same AHP model. As shown in the Figures, the main objective of such models is to determine the probability of failure and assess the contribution of each root cause as determinants for future prognostics and simulations. Root cause influence is based on historical data, experience, and previous knowledge and studies, such as Rossiter's et al. article (1991) and Noval's et al. article (2014). The main contributors to failure are the Act of God factor, the climate exposure phenomena, and the external interference factor, mainly equipment damage and abuse. As for the cementitious waterproofing, the AHP model diverts from that of the sheet and liquid-based components since the location of the application is unexposed to climate variation. Only humidity and seismic activities have a negative impact as an Act of

God factor. However, the major contributor, in this case, is the external interferences factor resulting from excessive mechanical and electrical machinery works and failures.

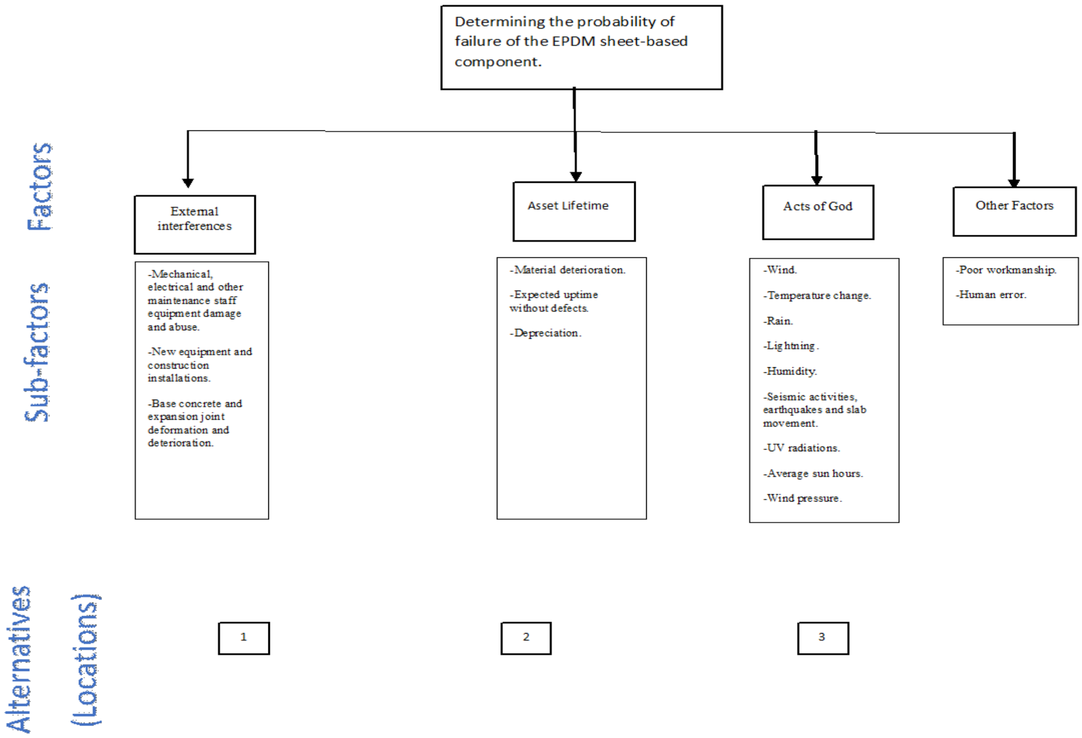


Figure 21 AHP model of the sheet-based component.

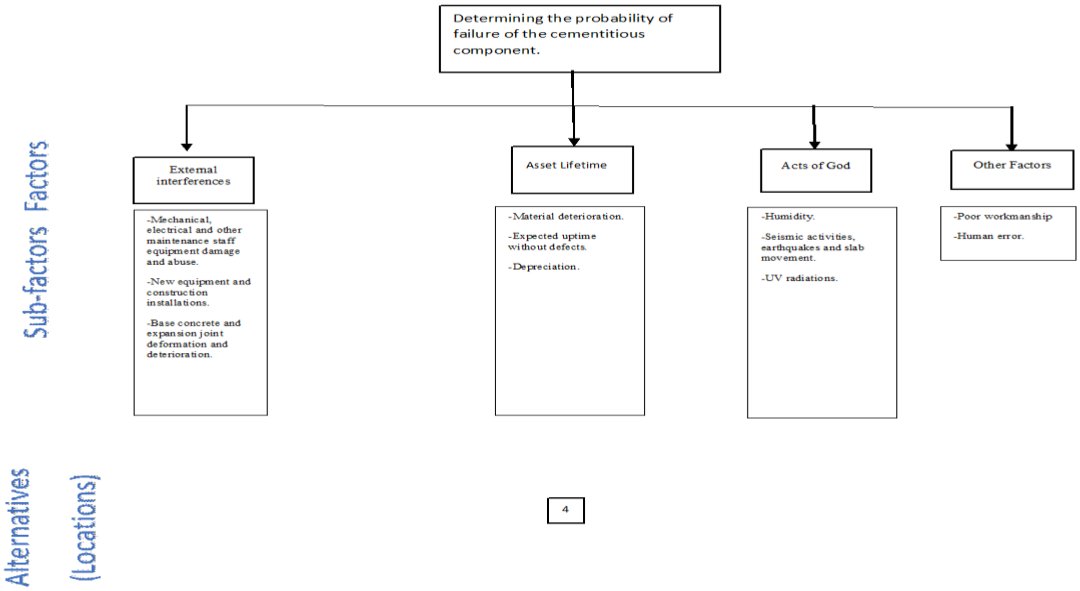


Figure 22 AHP model of the cementitious component.

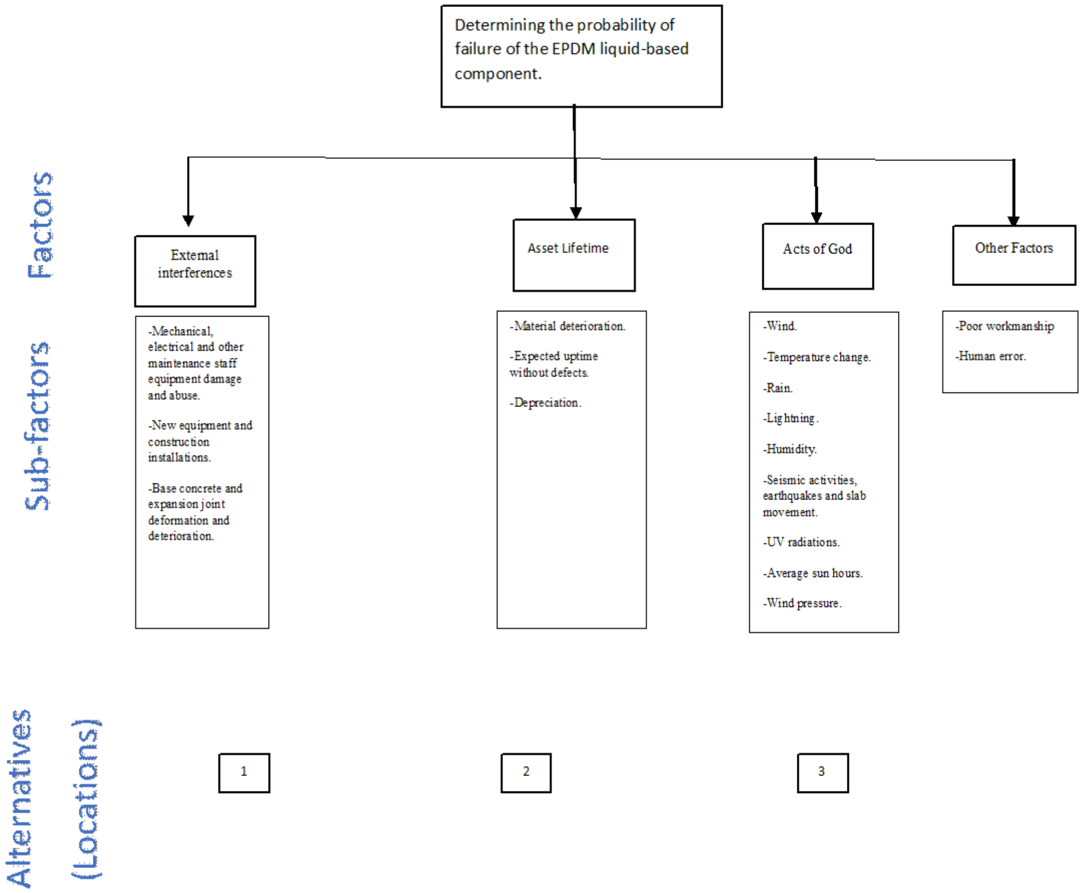


Figure 23: AHP model of the liquid-based component.

4.1.7 Data Collection

This research analyzes the failure probabilities of the three components in all four locations based on time since last failure (lifetime) and weather (external factors). The historical data duration was based on four years. In order to make this methodology as flexible as possible in low-data environments, an assumption was made that failure rates and scope can be extracted from material request orders designated for each location at the time of failure. When adopting such a data assumption, we lose the connection between the failures and root causes. However, the weather on the date of the request, along with the time interval from the previous request, can still serve as significant predictors of failure when coupled with a machine learning technique. Eight climate determinants were taken every day to consider their impact on the whole system. These weather variables are wind speed, maximum temperature, minimum temperature, average temperature, humidity, ultraviolet index, and average sun hour.

To determine the days from the last failure, the interval between maintenance request orders were studied. Table 11 shows the total number of request orders, locations, and areas of failure. On the basis of the data collected, several modeling decisions were made. First, Location 4 was excluded from the study – all cementitious material requests made in Location 4 were associated with an overhaul of all the mechanical rooms. This assumption was corroborated by the requests made for sheet-based waterproofing materials in the mechanical rooms-- a request that is only explained by the installation of new upstands requiring waterproofing protection.

Second, for the sheet-based waterproofing, requests were separated into base sheets and skirting types. Both will be included in the simulation but analyzed separately. Their base component is the same, but they defer in implementation, consequences of failure (both cost and area), repair and failure modes, and the total area of application.

Finally, liquid-based waterproofing materials were also excluded from the study since this material is applied only in a few tight areas, which makes requests for this material negligible in the data and incomparable to other components' data samples.

As a result, Tables 12, 13, and 14 provide a list of material requests for the sheet-based and skirting assets associated with the statistical summaries that are needed for simulation in Locations 1, 2, and 3, respectively. As the material requests are serving as a proxy for failure, we can say that Location 1 has the greatest number of failures, while Location 2 has the most failed area of the three locations. This slight variation of total failed areas between Locations 1 and 2 is likely due to the greater sun and ultraviolet radiation exposure present in Location 2 relative to Location 1. This finding is in keeping with Noval's et al. el Boquerón reservoir article (2014). Location 3 has the lowest failure count for sheet-based material and only one skirting failure. As a result, skirting failures in Location 3 will be excluded from the simulation as they would have no meaning whatsoever within the entire simulation.

Table 10: General overview of the request order failure type, location date of the requisition, and the total area of failure.

SN	TYPE	Location Category	Date	Area of Order (Pail/sqm)
1	Sheet-based	3	05-02-16	718

2	Sheet-based	2	09-03-16	638
3	Sheet-based	1	21-03-16	650
4	Sheet-based	1	31-03-16	383.5
5	Sheet-based	1	01-04-16	140
6	Sheet-based	1	07-04-16	325
7	Sheet-based	1	20-04-16	780
8	Sheet-based	1	26-04-16	530
9	Sheet-based	2	03-06-16	800
10	Skirting	4	28-06-16	90
11	Sheet-based	1	30-06-16	460
12	Sheet-based	2	13-08-16	850
13	Sheet-based	1	14-08-16	360
14	Sheet-based	2	30-08-16	400
15	Sheet-based	3	07-11-16	67
16	Sheet-based	3	03-12-16	99
17	Sheet-based	1	03-01-17	258
18	Sheet-based	1	16-02-17	177.76
19	Sheet-based	1	03-03-17	320
20	Sheet-based	2	06-03-17	250
21	Sheet-based	2	20-03-17	198
22	Sheet-based	1	28-03-17	415
23	Sheet-based/Skirting	2	29-05-17	150
24	Cementitious	4	29-06-17	20.82
25	Cementitious	4	11-07-17	20.82
26	Cementitious	4	07-08-17	52.05
27	Sheet-based	4	31-08-17	180
28	Sheet-based	3	12-09-17	99
29	Sheet-based	3	15-09-17	180
30	Sheet-based	4	03-01-18	45
30	Skirting	4	04-01-18	135
31	Sheet-based	3	29-01-18	45
32	Sheet-based	3	23-02-18	50
33	Skirting	1	18-04-18	40
34	Sheet-based	3	11-05-18	15
35	Cementitious	4	13-06-18	104.1
36	Sheet-based/Skirting	2	03-09-18	150
37	Sheet-based	2	21-09-18	110
38	Sheet-based	3	26-09-18	45
39	Skirting	3	31-01-19	60
40	Sheet-based	3	14-02-19	594
41	Sheet-based	1	12-03-19	20
42	Sheet-based/Skirting	1	25-03-19	20
43	Sheet-based/Skirting	1	05-04-19	225
44	Sheet-based/Skirting	1	18-04-19	140

45	Sheet-based	2	17-05-19	20
46	Cementitious	3	07-06-19	41.64
47	Cementitious	3	12-06-19	41.64
48	Cementitious	4	16-06-19	72.87
49	Sheet-based	2	03-07-19	180
50	Sheet-based	2	11-07-19	225
51	Skirting	2	24-07-19	180
52	Cementitious	4	31-07-19	208.2
53	Skirting	2	31-07-19	90
54	Cementitious	4	31-07-19	62.46
55	Sheet-based	2	05-08-19	93
56	Sheet-based/Skirting	2	04-09-19	225
57	Sheet-based/Skirting	1	18-09-19	465
58	Sheet-based/Skirting/Liquid-based	2	19-09-19	2Pail/465
59	Sheet-based	1	23-09-19	465
60	Cementitious	4	27-09-19	208.2
61	Sheet-based	3	30-09-19	100
62	Cementitious	4	02-10-19	374.76
63	Cementitious	4	01-11-19	114.51
64	Cementitious	4	18-11-19	104.1
65	Sheet-based	2	19-12-19	594
66	Sheet-based/Skirting	2	20-12-19	396

Table 11:Location 1's general statistical overview of the failures

Type	Area of Failure(sqm)	Average	Maximum	Minimum	Count
Sheet-based	650	322.6811111	650	4	18
	383.5				
	140				
	325				
	780				
	530				
	460				
	360				
	258				
	177.76				
	320				
	415				
	20				
	4				
	193				
	54				
	273				
	465				
Skirting	48	74.8	192	16	5
	16				

	32				
	86				
	192				

Table 12:Location2's general statistical overview of the failures

Type	Area of Failure(sqm)	Average	Maximum	Minimum	Count
Sheet-based	638	303.8235	850	20	17
	666				
	850				
	400				
	250				
	198				
	22				
	102				
	110				
	20				
	180				
	213				
	86				
	167				
	369				
	594				
	300				
Skirting	128	102	192	48	7
	48				
	192				
	96				
	58				
	96				
	96				

Table 13: Location3's general statistical overview of the failures

TYPE	Area of Failure(sqm)	Average	Maximum	Minimum	Count
Sheet-based	718	139.2222	718	15	11
	67				
	99				
	99				
	123				
	45				
	42				
	15				
	45				
	594				

	100				
Skirting	96	96	96	96	1

Now that the entire locations’ failure modes are known along with their dates, the “days from last failure” predictor can be introduced into the system. Tables 15, 16, 17, 18, and 19 show an overview of this predictor for each waterproofing type associated to each location.

Table 14: Days from last failures for sheet-based waterproofing at location1

SN	Area of failure	Date	DaysFromLastFail_Loc1_Sheet
1	650	21-Mar-16	81
2	383.5	31-Mar-16	10
3	140	01-Apr-16	1
4	325	07-Apr-16	6
5	780	20-Apr-16	13
6	530	26-Apr-16	6
7	460	30-Jun-16	65
8	360	14-Aug-16	45
9	258	03-Jan-17	142
10	177.76	16-Feb-17	44
11	320	03-Mar-17	15
12	415	28-Mar-17	25
13	20	12-Mar-19	714
14	4	25-Mar-19	13
15	193	05-Apr-19	11
16	54	18-Apr-19	13
17	273	18-Sep-19	153
18	465	23-Sep-19	5

Table 15: Days from last failures for skirting waterproofing at Location 1.

SN	Area of failure(sqm)	Date	DaysFromLastFail_Loc1_Skirting
1	48	18-Mar-18	808
2	16	25-Mar-19	372
3	32	05-Apr-19	11
4	86	18-Apr-19	13
5	192	18-Sep-19	153

Table 16: Days from last failures for sheet-based waterproofing at location 2.

SN	Area	Date	DaysFromLastFail_Loc2_Sheet
1	638	09-Mar-16	69
2	666	03-Jun-16	86
3	850	13-Aug-16	71
4	400	30-Aug-16	17

5	250	06-Mar-17	188
6	198	20-Mar-17	14
7	22	29-May-17	70
8	102	03-Sep-18	462
9	110	21-Sep-18	18
10	20	17-May-19	238
11	180	03-Jul-19	47
12	213	11-Jul-19	8
13	86	05-Aug-19	25
14	167	04-Sep-19	30
15	369	19-Sep-19	15
16	594	19-Dec-19	91
17	300	20-Dec-19	1

Table 17: Days from last failures for skirting waterproofing at location 2.

SN	Area	Date	DaysFromLastFail_Loc2_Skirting
1	128	29-May-17	515
2	48	03-Sep-18	462
3	192	24-Jul-19	324
4	96	01-Aug-19	8
5	58	04-Sep-19	34
6	96	19-Sep-19	15
7	96	20-Dec-19	92

Table 18: Days from last failures for sheet-based waterproofing at location 2.

SN	Area	Date	DaysFromLastFail_Loc3_Sheet
1	718	05-Feb-16	36
2	67	07-Nov-16	276
3	99	03-Dec-16	26
4	99	12-Sep-17	283
5	123	15-Sep-17	3
6	45	29-Jan-18	136
7	42	23-Feb-18	25
8	15	11-Apr-18	47
9	45	26-Sep-18	168
10	594	14-Feb-19	141
11	100	30-Sep-19	228

4.1.8 Determining the probability of failures from the designated root causes

The most critical parameter in the simulation is the probability of failure. This probability was derived in two-steps. First, a random forest predictive model serves to predict whether the asset in the given Location fails (1) or not (0). A separate random forest model was built for each Location using the weather and time since past failure as variables for all days in the past four years. The random forest is the most accurate tool amongst decision trees-- it combines several trees' efforts to act as a sole classification algorithm(Yiu, 2019).

As this full four-year dataset contains far fewer failure events than non-fail events, a synthetic dataset was created following the principles of the Synthetic Minority Oversampling Technique. The resulting dataset was then used as the basis for the random forest model. The quality of the random forest model built on the "SMOTed" data was subsequently tested on the actual study data.

Figures 24, 25, 26 show the variable importance in these models for the prediction of failure across Locations 1, 2, and 3, respectively. These Figures, along with Table 20, serve to confirm the importance of weather in predicting failure. Mainly we see that weather has a stronger influence on Location 2 than it does on Location 1 for which the main predictor of failure is the days since the last failure. These Figures also illustrate the differential impact of weather on sheeting versus skirting. Table 21 summarizes the accuracy, specificity, and no-information rate of the random forest models for Locations 1, 2, and 3.

Table 19: Top influencers of all types at all locations.

Location	Type	Top Influencers
1	Sheet	Sun Hour and Days from the Last Failure
	Skirting	Sun Hour and Minimum Temperature
2	Sheet	Humidity and Wind speed
	Skirting	Humidity and Wind speed
3	Sheet	Humidity and Days from the Last Failure

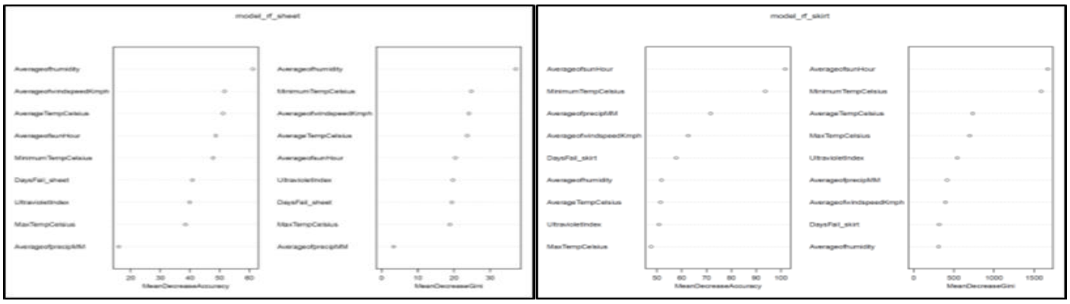


Figure 24: Variable importance in the Random Forest Model of sheet-based failure (left) and skirting failure (right) in Location 1.

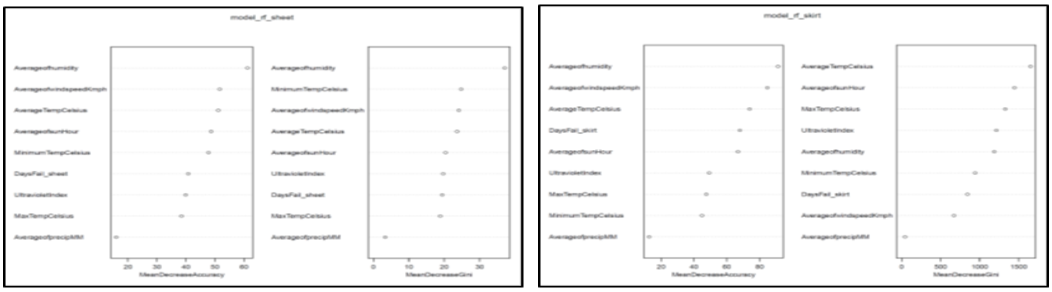


Figure 25: Variable importance in the Random Forest Model of sheet-based failure (left) and skirting failure (right) in Location 2.

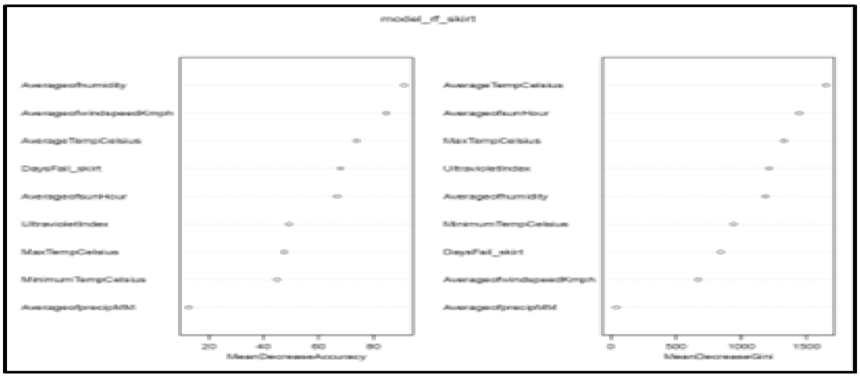


Figure 26: Variable importance in the Random Forest Model of sheet-based failure in Location 3.

The second step in analyzing the probability of failure is to determine the extent of failure. In analyzing the data on the square meters within each area, it was found that a Poisson distribution served as the best fit – which is also logical as Poisson distributions describe rates of occurrence. Table 22 represents the lambda parameters (λ) derived from past data for each location and type of material.

Table 20: Accuracy, specificity, and no-information rate for each Location and type.

Location	Material Type	Accuracy	Specificity	No-Information Rate
1	Sheet	0.9945	1	0.9877
1	Skirting	1	1	0.9966
2	Sheet	0.9945	1	0.9884
2	Skirting	1	1	0.9952
3	Sheet	0.9993	1	0.9925

Table 21: Lambda parameter for each type and location.

Locations	Type	Lambda parameter(λ)
1	Sheet-based	331
	Skirting	178
2	Sheet-based	304
	Skirting	102

3	Sheet-based	177

4.1.9 Assessing the consequences of failures

This part analyzes all damage costs that come with water leakage. Humidity and water penetration can be immensely destructive to the system’s durability and functionality. Severe damage can result from just simple drops of water coming down from the roof. Since this model provides a multi-objective approach, the consequences are divided into two distinct categories. The first is the direct cost, which is anything that has to do with the actual construction and finishing damages requiring rectification to retain the facility’s original structure and finishing. This consists of the following: roofing expansion joints and concrete as first-order damage, then comes the false ceiling as second-order damage, and finally, the paint and tile, which provide the architectural finishing of the airport. Table 23 demonstrates the expense of having such damages for each type of waterproofing separately. Sheet-based waterproofing has a higher direct damage cost than that of the skirting.

The second category is the indirect cost associated with such damages. These can be reputation, safety, condition, competitive disadvantage, time wasted, penalties, etc. As for this case study, only safety and reputation costs were included. This choice was made on the basis that an airport is a public facility that reflects on multiple sectors within a country – tourism, trade, transportation, etc. Table 24 illustrates the list of indirect costs based on the locations in the study. Location 1 and 2 provide extensive reputation and safety costs since failures can be seen by the public, which adds to the reputation cost. The existence of several mechanical rooms and heavy machinery, as well as the crowded areas of the public areas, infer a heavy safety and wellbeing cost in the case of water leakage. The numbers provided were computed based on experience. As a result, the total consequence cost is presented in Table 25 as the sum of both the direct and indirect costs.

Table 22: Direct costs per sqm of failure.

Type	1st order damage($/sqm)	2nd order damage($/sqm)	3rd order damage($/sqm)	Total cost ($/sqm)
EPDM sheet	80%joint damage+20%concrete damage	False Ceiling=0.33	Floor Tile and paint damage=0.78	1.7

	=0.8*60+0.2*50= 0.58			
Skirting	Concrete damage=0.5	False Ceiling=0.33	Tile (skirting and floor) +Paint=36.7+27=0.637	1.48

Table 23: Indirect safety and reputation costs per sqm of failure.

Location	Type	Reputation and safety added costs ($/sqm)
1	EPDM sheet	1.5
	Skirting	1.5
2	EPDM sheet	1.5
	Skirting	1.5
3	EPDM sheet	1
	Skirting	1

Table 24:Total consequences cost per sqm of failure.

Location	Type	Asset damage consequences ($)	Reputation and safety added costs ($)	Total ($)
1	EPDM sheet	1.7	1.5	3.2
	Skirting	1.48	1.5	2.98
2	EPDM sheet	1.7	1.5	3.2
	Skirting	1.48	1.5	2.98
3	EPDM sheet	1.7	1	2.7
	Skirting	1.48	1	2.48

4.2 Step 2: Interpreting the total risk

4.2.1 Total Risk

As a subsequent step, the absolute failure risk will be analyzed based on the provided information from the previous findings. As mentioned before, the formula is as follows:

$$R_T = C_{Repl}*t/useful\ life + C_O*t + C_{PM}*t/T + P_f*C_f$$

The total risk will be calculated for the filtered categories listed in the previous step. Those categories are as follows: Location 1 sheet-based, location 1 skirting, Location 2 sheet-based, Location 2 skirting, and Location 3 sheet-based.

4.2.2 Derivation of parameters

4.2.2.1 Useful Life

The useful life is estimated to be 25 years for all categories. It is directly related to the type of waterproofing structure and its reliability period, thus having the same component in all locations will not affect the useful life making it a constant value over the three locations.

4.2.2.2 Cost of replacement (C_{Repl})

The cost of replacement is the total cost associated with replacing the asset after fully accomplishing its useful life. It is directly related to the type of waterproofing and the total area of the location. This element will be studied as a lumpsum amount at each location. First off, is the expense of waterproofing for each type, which in this case are the sheet and skirting. Both items are very similar and consist of the same component. However, the skirting is special through its unique flashing design on parapets and edges that permits water from entering through the top, and the base sheet is differentiated through its unexposed design due to the heat insulation and cement tile protections. Each unit of the base sheet has an area total of 99 sqm, consisting of a 33-meter length and a 3-meter width. As for the skirting, each unit has a 33-meter length and a width of 40 centimeters, 20 centimeters to cover the vertical parapets and edges, and 20 centimeters that provide the overlapping to the base sheet structure(as shown in Figure 27). Thus, each unit would provide a total area of 13.2 sqm. The cost of replacement is then divided into two parts the cost of materials and the cost of labor. Tables 25 provide all adhesive and implementation

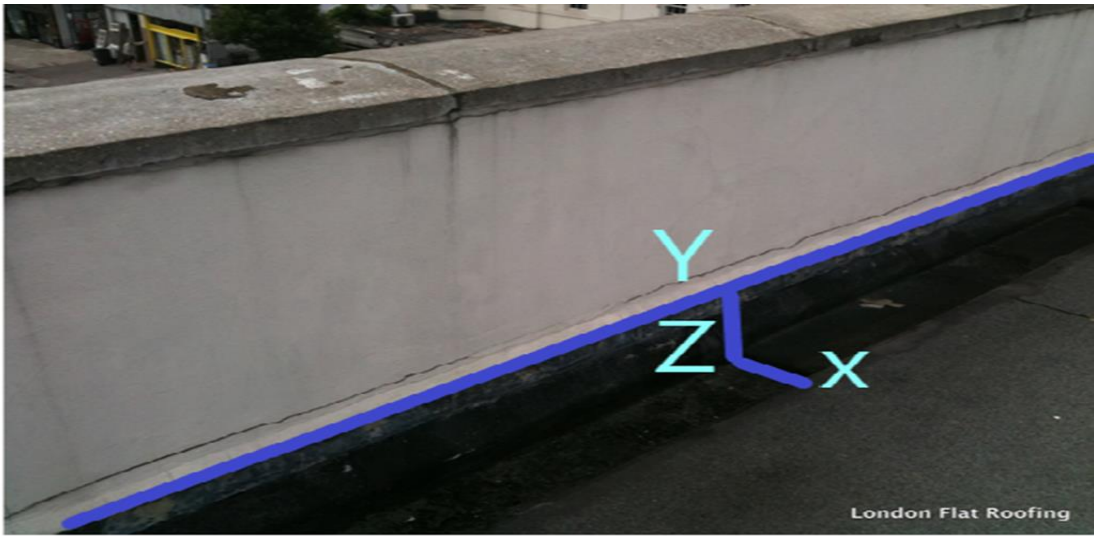


Figure 27: is a picture showing the skirting design. X, Y, and Z represent the distances for overlapping, length, and vertical parapet and edges application(D, 2010).

materials' properties and costs for both types. Table 26 shows the added materials of the skirting type to that of table 25 for closing in on the parapets and edges.

Table 25: The detailed material specs and prices needed for both types of EPDM waterproofing.

SN	Item Description	Item Properties and specs.	Unit	Unit Price ($)	Unit Coverage
1	Carlisle "Sure-Seal" EPDM (Sheet)	A roofing membrane that is a non-reinforced Ethylene Propylene Diene monomer (EPDM)-based elastomeric homogenous roof coverings.	3x30m/Roll	22.5/sqm	99sqm
2	Carlisle "Sure-Seal" EP-95 Splicing Cement	Synthetic rubber splicing cement used to splice the EPDM sheet to another and the skirting at the edges and parapets. To provide a deep protection form penetration at joints between the sheets(Carlisle Syntec Systems, 2015a).	1USG/Pail	147/Pail	36lmx100mm (3.6sqm for 100mm jointing between 2 EPDM sheets)
3	Carlisle "Sure Seal 90-8-30A Bonding" Adhesive	Carlisle's 90-8-30A Bonding Adhesive is a high-strength, solvent-based contact adhesive. It enables the bonding of an EPDM sheet to the concrete or screed surface(Carlisle Syntec Systems, 2017).	5USG/Pail	345/Pail	27.5 sqm
4	Carlisle "Sure-Seal" Lap Sealant	A gun-consistency material Seals the exposed edges of the EPDM sheet to prevents dust and moisture from penetration. It has an amazing capability of expanding and contracting with the EPDM sheets(Carlisle Syntec Systems, 2016).	326ml/tube	21.85/tube	5.8 meters

Table 26: Added materials for skirting applications.

SN	Item Description	Item Properties and specs.	Unit	Unit Price ($)	Unit Coverage
1'	Carlisle "Sure-Seal" Termination bar (FLASHTITE)	Aluminum bars for securing and sealing flashing terminations on the top edge of the skirting(Carlisle Syntec Systems, 2015b).	25mmwidex3mmthickx3m	18/Strip	3 meters

2’	Dymonic FC Sealant	“A high-performance, fast-curing, single-component, low modulus, hybrid sealant, formulated with proprietary silane end-capped polymer technology”(TREMCO Commercial Sealants and Waterproofing, 2020, p. 1). It is spread on the top edges of the FLASHTITE aluminum bars for extreme protection.	600ml Sausage	10/Sausage	8 meters

Now that the cost of materials is recognized, the cost of materials per unit and sqm of both the base sheets and the skirting is calculated. Table 27 shows the cost of the materials needed for sheet and skirting installation. The next part of the replacement cost is the cost of the labor needed to accomplish the application. Table 28 shows the total cost of workmanship implementation. Considering the heavyweight of the sheet, more laborers are needed for the application of the base sheets than the skirting. After computing both elements of the replacement cost, lump sum values are derived for all 3 locations (as shown in Table 29).

Table 27: Sheet and skirting detailed material cost calculation

SN	Type	Material cost equations (From tables 24 and 25)	Total Material Cost/unit ($)	Total Material Cost/sqm ($)
1	EPDM Sheet Based	1+2+3+4	4032.38	40.73
2	Skirting	1+2+3+4+1'+2'	1090	82.57

Table 28: Sheet and skirting detailed labor cost calculations.

SN	Type	Unit coverage of each(sqm)	Work Force/unit	Total Workforce Cost/unit ($)	Total workforce cost/sqm ($)
1	EPDM Sheet Based	99	One technician, two labors, and one supervisor	280.5	2.83
2	Skirting	13.2	One technician and one supervisor	105	7.95

Table 29: Total Cost of replacement at each location.

Locations	The total cost of Replacement for EPDM sheet ($)	The total cost of replacement for EPDM skirting ($)	Total ($)
1	762397.7273	27883.33333	790281.1
2	762397.7273	27883.33333	790281.1
3	909109.8485	39109.09091	948218.9

4.2.2.3 Operating cost (C_O)

As mentioned before, the operating cost is negligible, as all waterproofing maintenance tasks are executed when the EPDM is least operational, and that is when there is no water during the process. Thus, like downtime, the value tends to be very negligible or even nonexistent during the maintenance process of waterproofing structures.

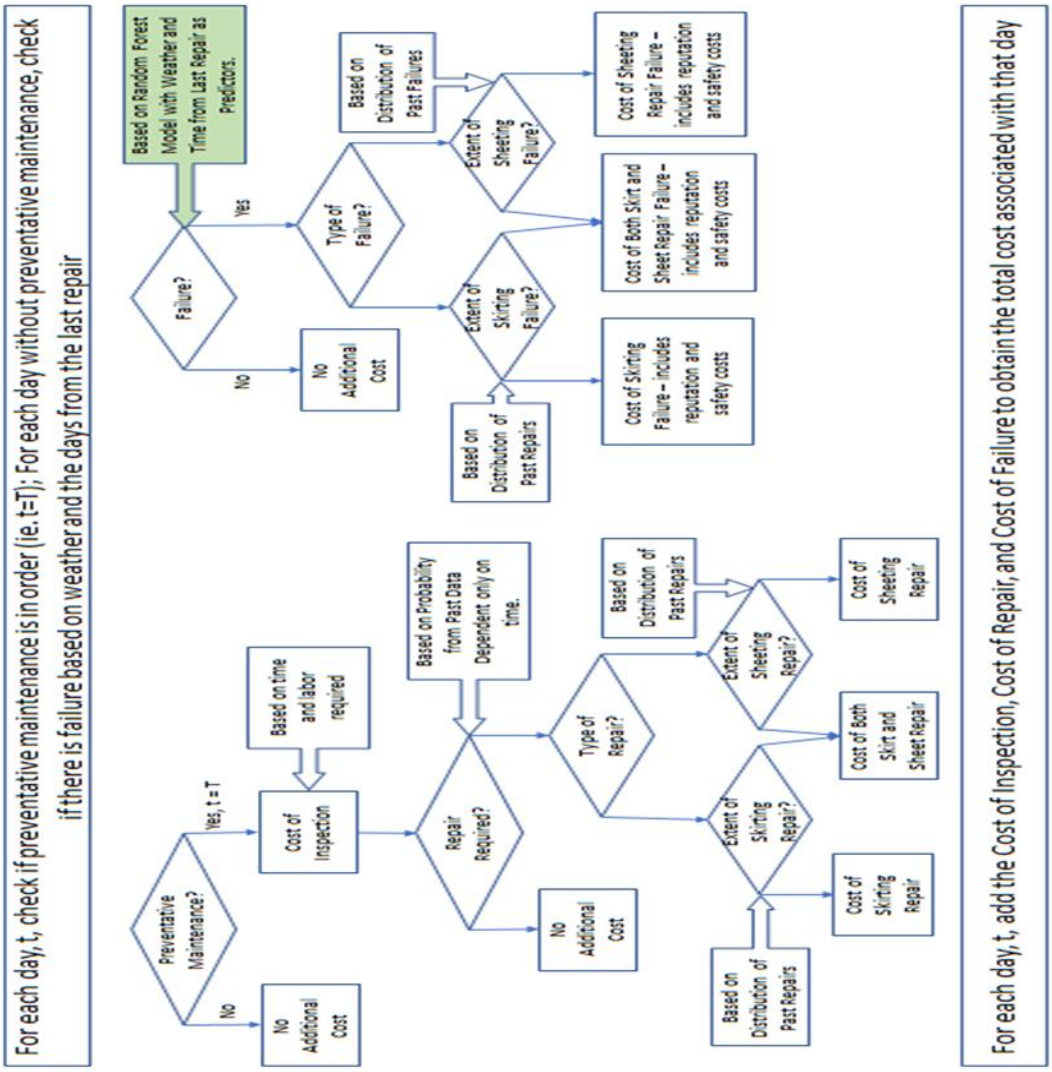


Figure 28: Decision tree model for simulation.

4.2.2.3 Probability of Failure (P_f)

The probability of failure is derived from the random forest predictive model described in Section 4.1.8. The diagram in Figure 28 illustrates how these probabilities are used within the simulation.

4.2.2.3 Failure costs (C_F)

This item is the cost of all damages associated with water leakage in a multi-objective model. The cost of failure is the sum of both the cost of replacing the defected asset and the consequences' expenses based on each location and type (As shown in table 30).

Table 30: Total failure cost as per location and type of waterproofing.

Location	Type	Total Consequences ($)	Cost of Replacement/sqm	Total Failure Cost/sqm
1	EPDM sheet	3.2	43.56060606	46.76060606
	Skirting	2.98	90.53030303	93.51030303
2	EPDM sheet	3.2	43.56060606	46.76060606
	Skirting	2.98	90.53030303	93.51030303
3	EPDM sheet	2.7	43.56060606	46.26060606

4.2.2.5 Preventive maintenance time intervals (T):

This is the maintenance policy's scheduled duration for preventive maintenance. Currently, this system does not have a preventive maintenance policy, thus the time interval between such nonexistent activities is infinite at this stage. However, in the simulation, several preventive maintenance intervals for several maintenance policies will be tested. Specifically, we will examine 15 days, 30 days, 60 days, 90 days, 120 days, 150 days, 180 days, 240 days, 300 days, and 360-day policies, along with a 1000 day policy to simulate the baseline corrective maintenance only policy.

4.2.2.6 Preventive maintenance cost (C_{PM})

This item is the cost of maintaining the asset of the system. It is divided into two categories: the cost of repair and the inspection cost. Some facilities consider proactive maintenance as the most important, while others might focus on a corrective or run to fail strategy. In terms of the cost of repair, we will study both high-cost repair and low-cost repair scenarios on the basis of a three-level and a four-level condition rating system, respectively. In this way, we can imagine high-cost preventive maintenance, defined by three conditions. The first condition is of excellent rating (no action is needed). The second would be fair, where preventive maintenance is required, and the defected sheet would be entirely replaced. Lastly would be poor, where the asset fails, and the defected sheet would be entirely replaced along with added failure consequences costs through corrective maintenance. A high-cost scenario is one where preventive maintenance is only undertaken when Rating 3 is achieved. Whereby a four-condition rating list defines a low-cost repair scenario. Likewise, the first condition would be of excellent rating. Whereas, in this type, both the second condition and the third condition resemble the preventive maintenance implementation module. It is unnecessary to replace the entire EPDM unit during repair, but certain tasks are applicable to provide a solution to the defect. Thus, the second condition resembles a fair rating, where inexpensive tasks come in handy to repair the defect. While, the third condition is of a bad rating, where a replacement of a unit is well advised. Finally, the last condition shows a poor rating that resembles the failure of the system. Tables 31 and 32 show a three-condition and a four-condition rating list for high-cost and low-cost repair scenarios, respectively. Providing a low-cost preventive maintenance strategy can diminish the repair cost to half that of a high-cost scenario. As for the inspection cost, it is the cost associated with inspecting the asset in order to find defects for failures and then do the repair if required. It is directly proportional to the area of the entire Location but does vary between the base sheet and skirting types. Due to the complexity of the unexposed base sheet, a hefty inspection cost is associated with base sheets compared to that of the exposed skirting.

Table 31: A condition rating system for the high-cost preventive maintenance scenario.

Rating	Basis	Action Required
1	Excellent condition, no failures were found; the system works properly, etc.	No action is required.

2	Fair condition, defects were like small visible cracks, damaged skirting and flashing, discoloration, defected EPDM sheets, etc. A preventive maintenance strategy to replace the unit	Preventive maintenance to replace the unit before failure.
3	Poor condition. Substantial failures, water leakage, defected waterproofing, damaged skirting and flashing, signs of corrosion, steel bars' exposure, etc.	Corrective maintenance.

Table 32: A condition rating system for the low-cost preventive maintenance scenario.

Rating	Basis	Action Required
1	Excellent condition, no failures were found; the system works properly, etc.	No action is required.
2	Fair condition, defects were like small visible cracks, damaged skirting and flashing,	Preventive maintenance to repair small defects, but does not require total unit replacement
3	Bad Condition, massive defects were found, significant cracks, discoloration, significant damages to the unit; the unit is about to fail, etc.	Preventive maintenance to replace the unit before failure.
4	Poor condition. Substantial failures, water leakage, defected waterproofing, damaged water, damaged skirting and flashing, signs of corrosion, and steel bars' exposure, etc.	Corrective maintenance.

However, the repair activity is inconsistent, and defects do not essentially appear every time an inspection goes through. Thus, due to the newly implemented preventive maintenance system, repair probability is deduced from the probability of having a failure probability through the years of study. Tables 33 and 34 show the inspection cost and probabilities cost of repair for each location and type for the high-cost preventive strategy and the low-cost preventive strategy, respectively.

Table 33: Repair cost overview for high-cost maintenance.

Location	Type	Cost of Repair/sqm	Probability of Repair at a time (t)	Inspection Cost
1	EPDM sheet	43.56060606	0.001	6364.363636
	Skirting	90.53030303	0.0003	46.66666667
2	EPDM sheet	43.56060606	0.001	6364.363636
	Skirting	90.53030303	0.00048	46.66666667
3	EPDM sheet	43.56060606	0.0007	7589.090909

Table 34: Repair cost overview for low-cost maintenance.

Location	Type	Cost of Repair/sqm	Probability of repair	Inspection Cost
1	EPDM sheet	22	0.001	6364.363636
	Skirting	45	0.0003	46.66666667
2	EPDM sheet	22	0.001	6364.363636
	Skirting	45	0.00048	46.66666667
3	EPDM sheet	22	0.0007	7589.090909

4.3 Step 3: Identify Optimal Maintenance Plan via Simulation

In this step, RStudio is used as an automation tool for simulation. R studio is the application that provides the visual interface for R script, which is a series of commands that one can use to produce several prognostic simulations for analysis efficiently(R Core Team, 2019). The main objective of the simulation is to provide insight into the optimal maintenance strategy to reduce both failure and total maintenance costs. The interface will simulate both waterproofing types at different locations, separately, through implementing the preventive maintenance scenarios. Both the high-cost and low-cost scenarios were tested across multiple maintenance intervals (*T*): 15, 30, 60, 90, 120, 180, 240, 300,360, and 1000 days. The thousand-day duration resembles a corrective maintenance-only strategy. The total duration for each simulation run is three years – since failures are “rare events” this horizon is necessary to smooth out anomalous events. Furthermore, each preventive maintenance interval was run 100 times to capture weather-related variations throughout the simulated years. Table 36 provides a summary of all simulation runs.

Table 35: Number of simulation runs.

Simulation number	Location	Maintenance cost	Preventive maintenance interval (T)
1	1	Low-cost	15

			30
			60
			90
			120
			180
			240
			360
			1000
2	2	High-cost	15
			30
			60
			90
			120
			180
			240
			360
			1000
3	1	Low-cost	15
			30
			60
			90
			120
			180
			240
			360
			1000
4	2	High-cost	15
			30
			60
			90
			120
			180
			240
			360
			1000
5	3	Low-cost	15
			30
			60
			90
			120
			180
			240
			360
			1000
6	3	High-cost	15

			30
			60
			90
			120
			180
			240
			360
			1000

4.3.1 Model Validation

After simulating all locations, the following results were obtained. All Tables (37-42) and Figures (29-34) that follow provide a general overview of the variation of the preventive, corrective, and total maintenance costs based on each time interval.

Table 36: Average of the 100 simulation results for Location 1 low-cost preventive scenario.

Preventive Maintenance Intervals	Average of Repair Costs(Million $)	Average of Fail Costs (Million $)	Average of Total Cost(Million $)
15	47.11	56.00	112.56
30	23.67	62.47	95.59
60	12.11	64.95	86.51
90	8.11	65.19	82.75
120	6.27	63.23	78.95
180	4.40	64.93	78.77
240	2.25	57.67	69.37
300	2.40	68.78	80.63
360	2.44	63.54	75.43
1000	0.00	49.87	59.32

Table 37: Average of the 100 simulation results for Location 1 high-cost preventive scenario.

Preventive Maintenance Intervals	Average of Repair Costs(Million $)	Average of Fail Costs (Million $)	Average of Total Cost(Million $)
15	46.29	56.00	111.74
30	23.16	62.47	95.09
60	11.62	64.95	86.02
90	7.75	65.19	82.39
120	5.84	63.23	78.52
180	3.92	64.93	78.29
240	1.97	57.67	69.09
300	1.98	68.78	80.22
360	1.99	63.54	74.98
1000	0.00	49.87	59.32

Table 38: Average of the 100 simulation results for Location 2 high-cost preventive scenario.

Preventive Maintenance Intervals	Average of Repair Costs(Million $)	Average of Fail Costs (Million $)	Average of Total Cost(Million $)
15	46.90	16.10	72.45
30	23.87	19.30	52.63
60	12.36	23.25	45.06
90	8.31	26.98	44.74
120	6.22	28.27	43.93
180	4.12	30.37	43.94
240	2.01	29.52	40.99
300	2.08	29.96	41.49
360	2.07	32.54	44.05
1000	0.00	31.32	40.77

Table 39: Average of the 100 simulation results for Location 2 low-cost preventive scenario.

Preventive Maintenance Interval	Average of Repair Costs(Million $)	Average of Fail Costs (Million $)	Average of Total Cost(Million $)
15	46.26	16.10	71.81
30	23.19	19.30	51.94
60	11.65	23.25	44.35
90	7.78	26.98	44.21
120	5.83	28.27	43.55
180	3.89	30.37	43.71
240	1.94	29.52	40.91
300	1.94	29.96	41.35
360	1.94	32.54	43.93
1000	0.00	31.32	40.77

Table 40: Average of the 100 simulation results for Location 3 high-cost preventive scenario.

Preventive Maintenance Intervals	Average of Repair Costs(Million $)	Average of Fail Costs (Million $)	Average of Total Cost(Million $)
15	55.12	3.16	69.62
30	27.76	6.53	45.62
60	13.97	8.68	33.99
90	9.36	8.83	29.52
120	7.03	8.69	27.06
180	4.80	8.91	25.05
240	2.61	8.92	22.86
300	2.45	10.52	24.31
360	2.32	10.38	24.03
1000	0.00	10.65	21.99

Table 41: Average of the 100 simulation results for Location 3 low-cost preventive scenario.

Preventive Maintenance Intervals	Average of Repair Costs(Million $)	Average of Fail Costs (Million $)	Average of Total Cost(Million $)
15	54.71	0.69	66.74
30	27.38	3.09	41.81
60	13.71	4.24	29.29
90	9.17	3.22	23.73
120	6.88	3.10	21.32
180	4.60	3.80	19.73
240	2.32	4.21	17.86
300	2.30	5.18	18.82
360	2.28	5.69	19.31
1000	0.00	6.10	17.44

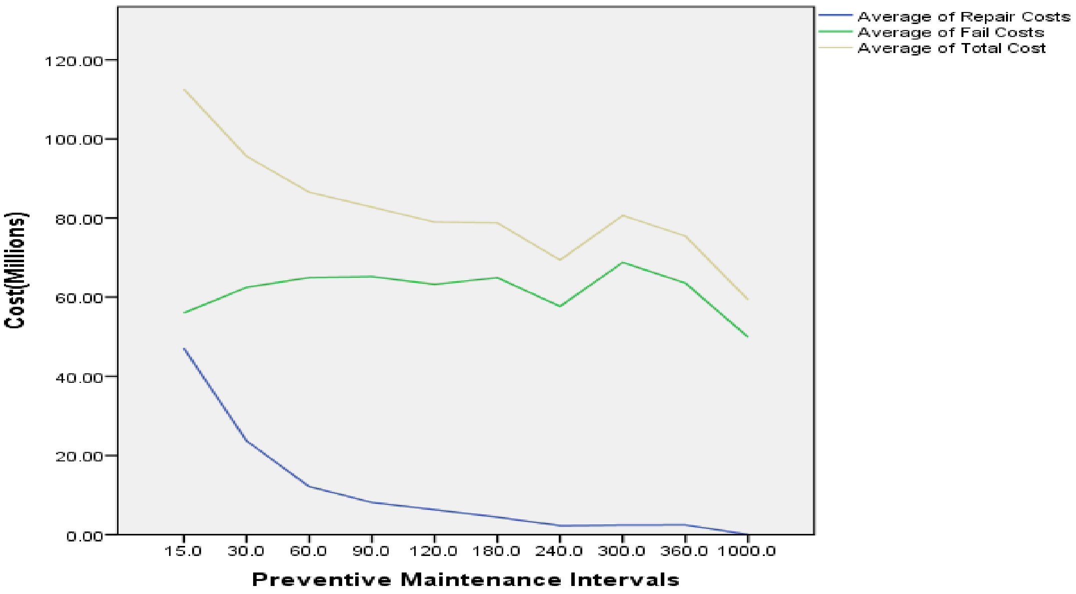


Figure 29: Variation of repair, failure, and total costs for Location 1 high-cost preventive maintenance scenario.

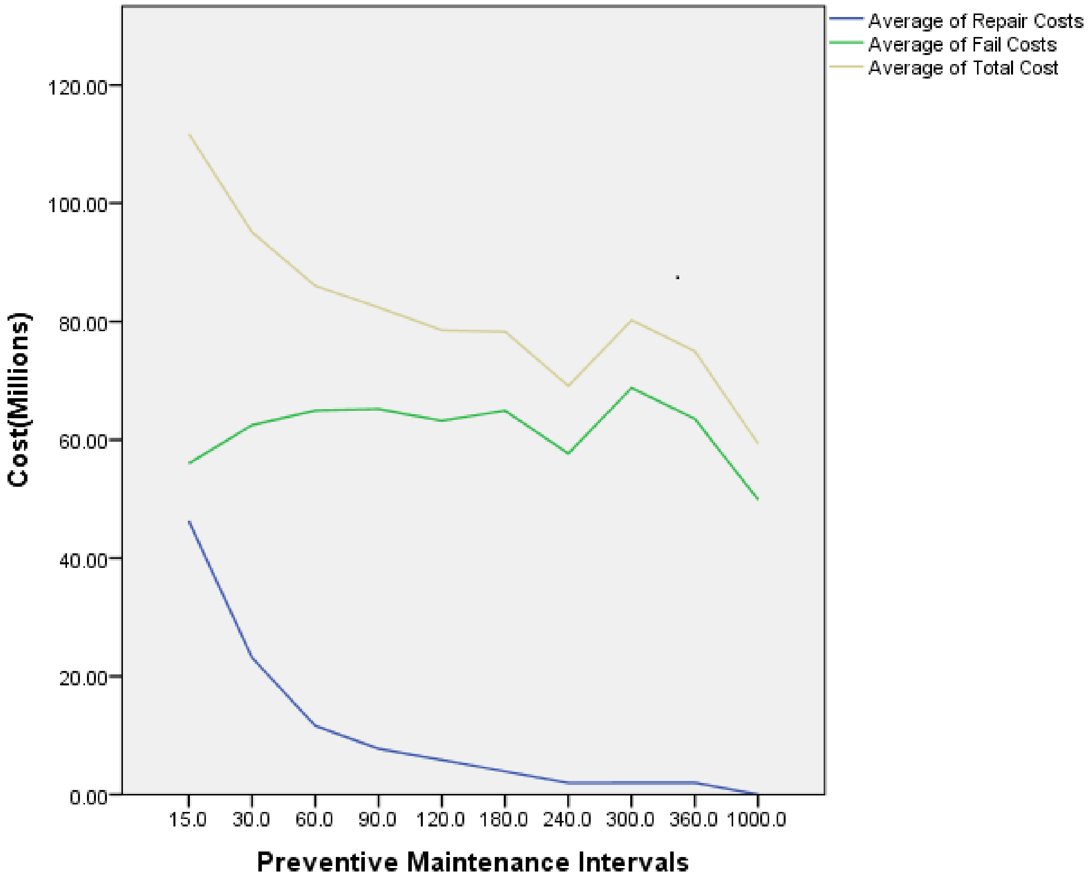


Figure 30: Variation of repair, failure, and total costs for Location 1 low-cost preventive maintenance scenario.

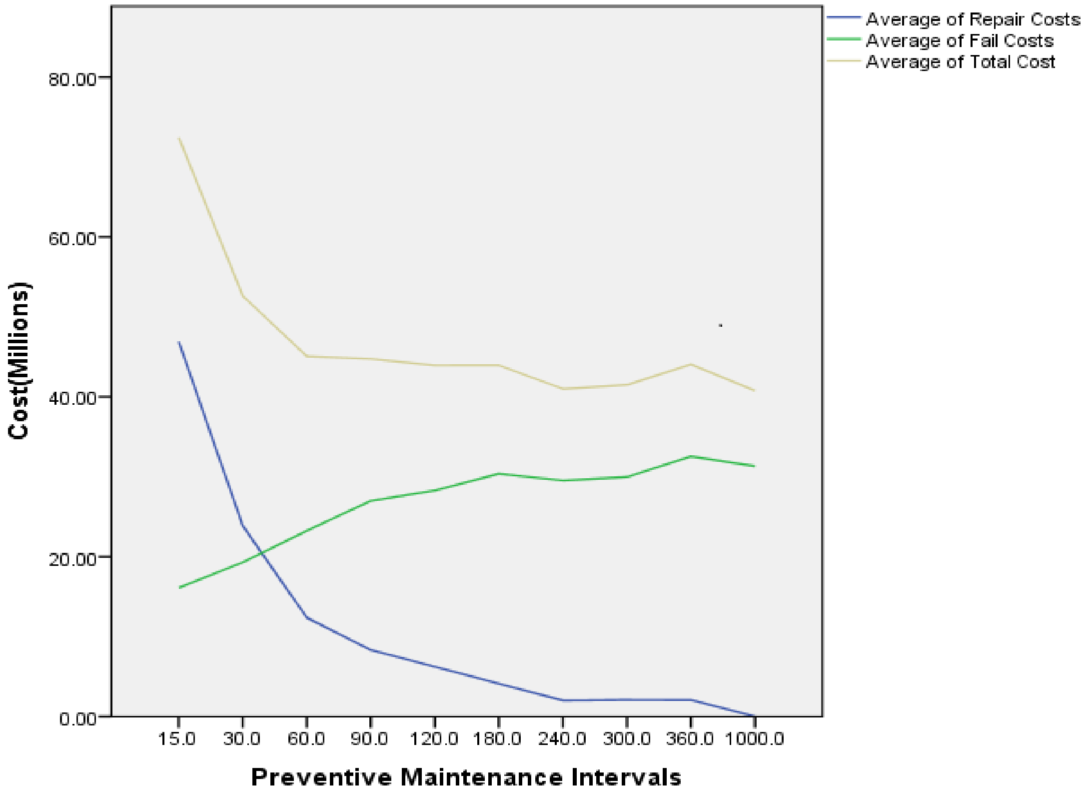


Figure 31: Variation of repair, failure, and total costs for Location 2 high-cost preventive maintenance scenario.

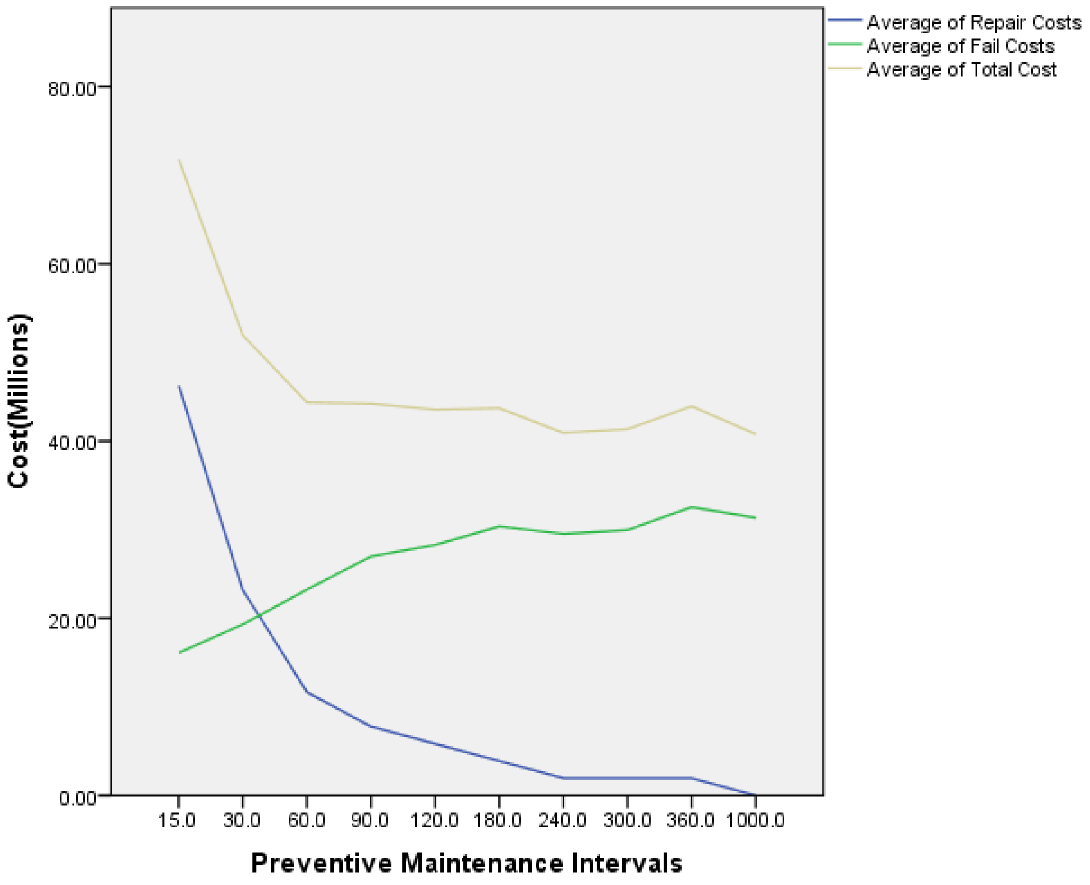


Figure 32: Variation of repair, failure, and total costs for Location 2 low-cost preventive maintenance scenario.

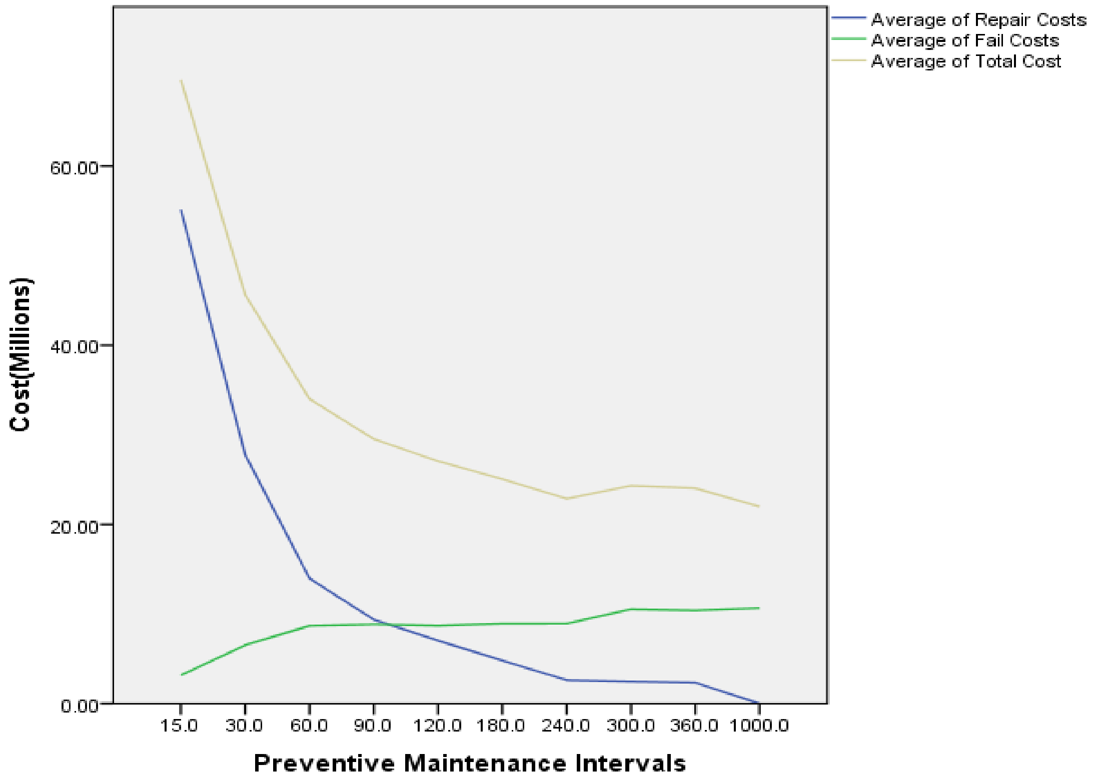


Figure 33: Variation of repair, failure, and total costs for Location 3 high-cost preventive maintenance scenario.

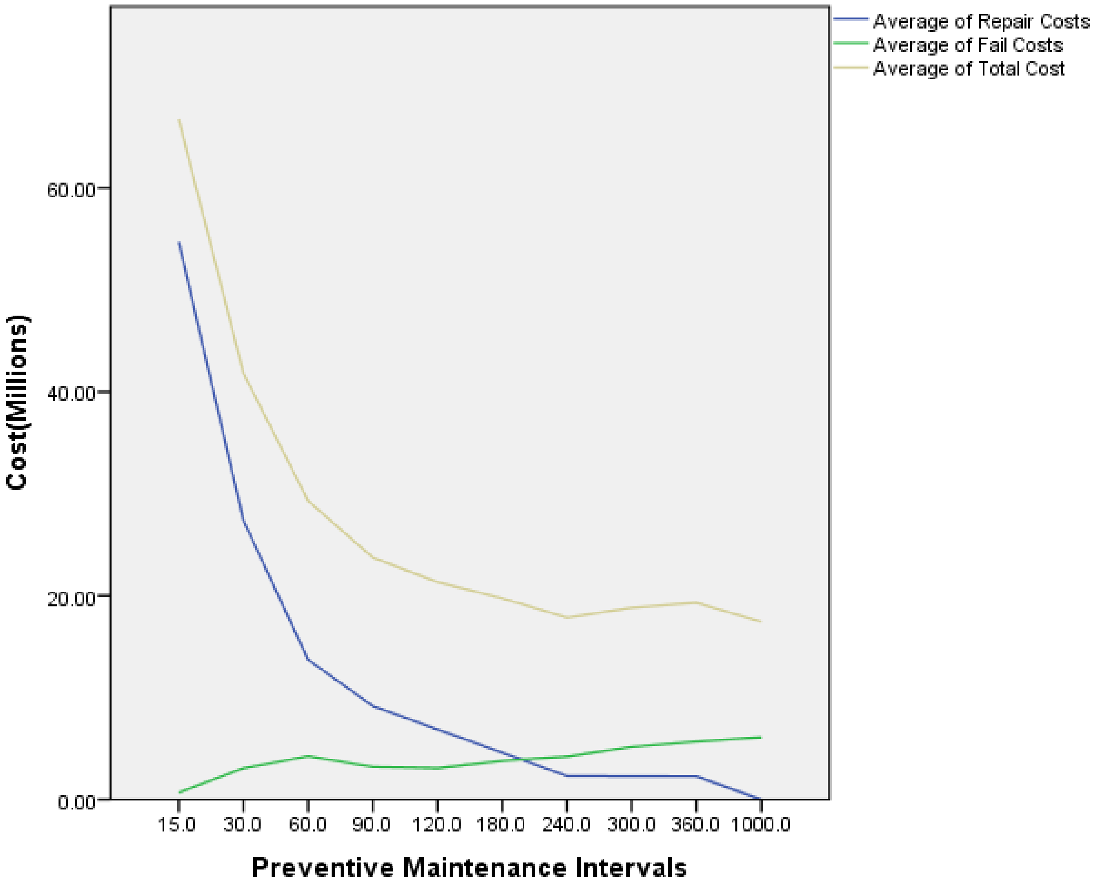


Figure 34: Variation of repair, failure, and total costs for Location 3 low-cost preventive maintenance scenario.

Figures 35-46 are the boxplots that show the preventive maintenance influence on failure cost and total cost. Figures 35-36 represent that of Location 1 high-cost preventive maintenance, and Figures 37-38 are for low-cost preventive maintenance. While Figures 39-40 are for location 2 high-cost preventive maintenance and Figures 41-42 for low-cost preventive maintenance. Lastly, Figures 43-44 are for Location 3 high-cost and 45-46 for low-cost.

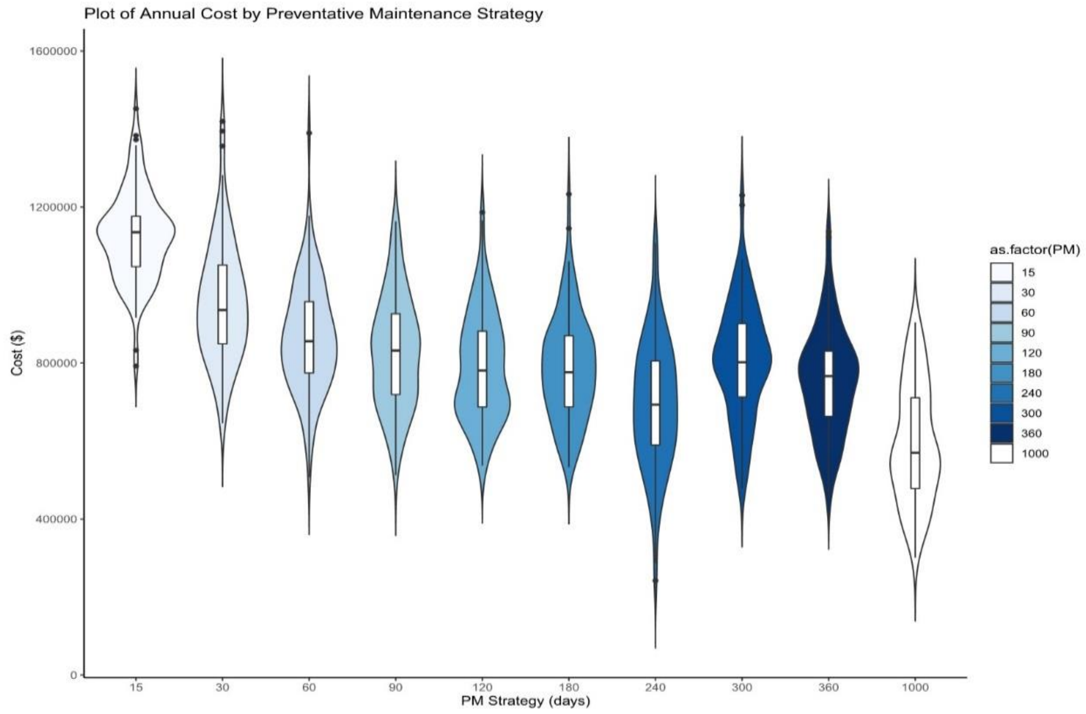


Figure 35: High-cost preventive maintenance strategy influence on annual cost in Location 1.

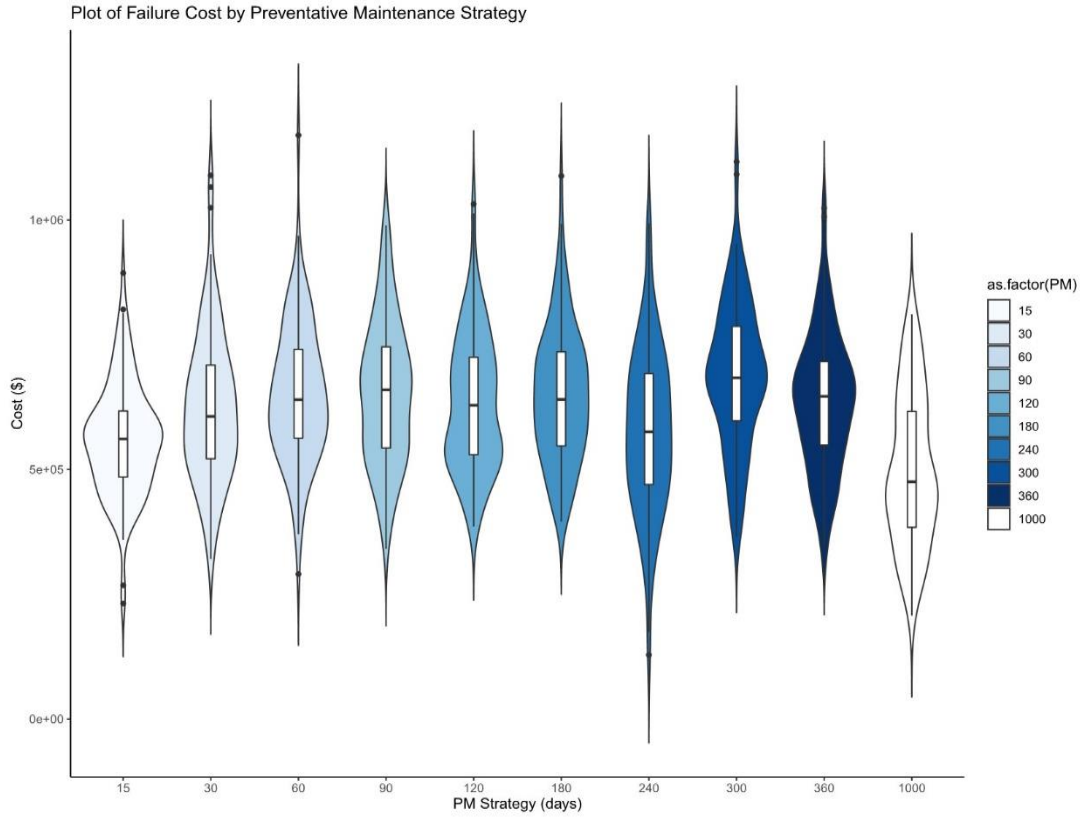


Figure 36: High-cost preventive maintenance strategy influence on failure cost in Location 1.

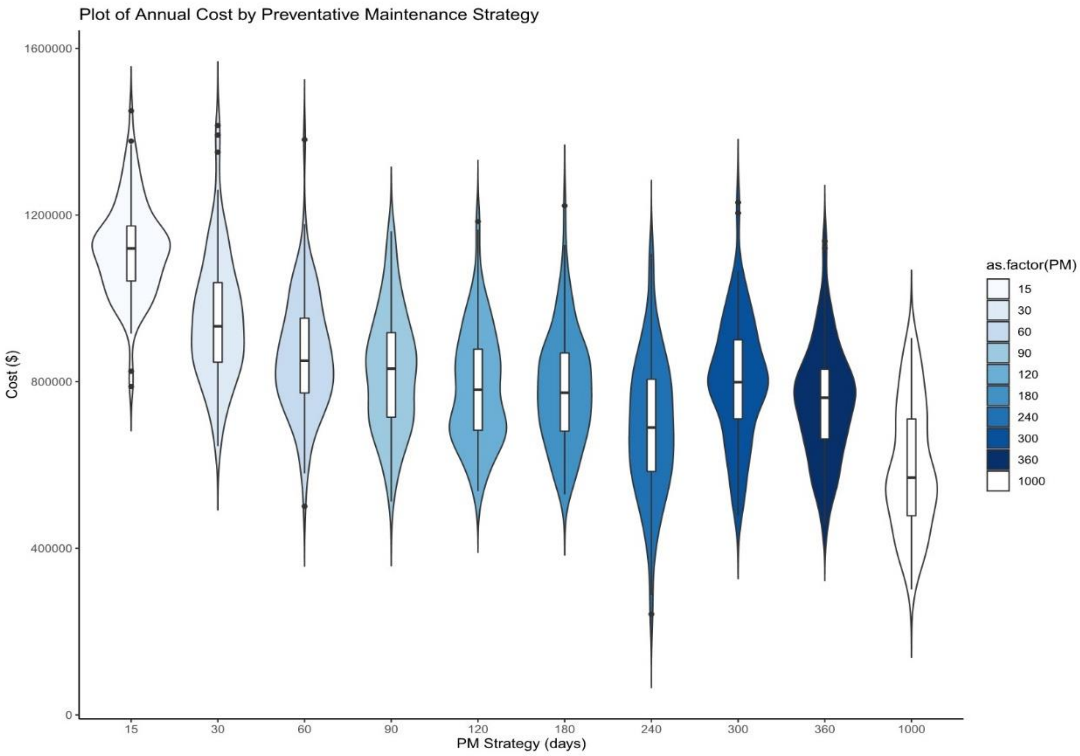


Figure 37: Low-cost preventive maintenance strategy influence on annual cost at Location 1.

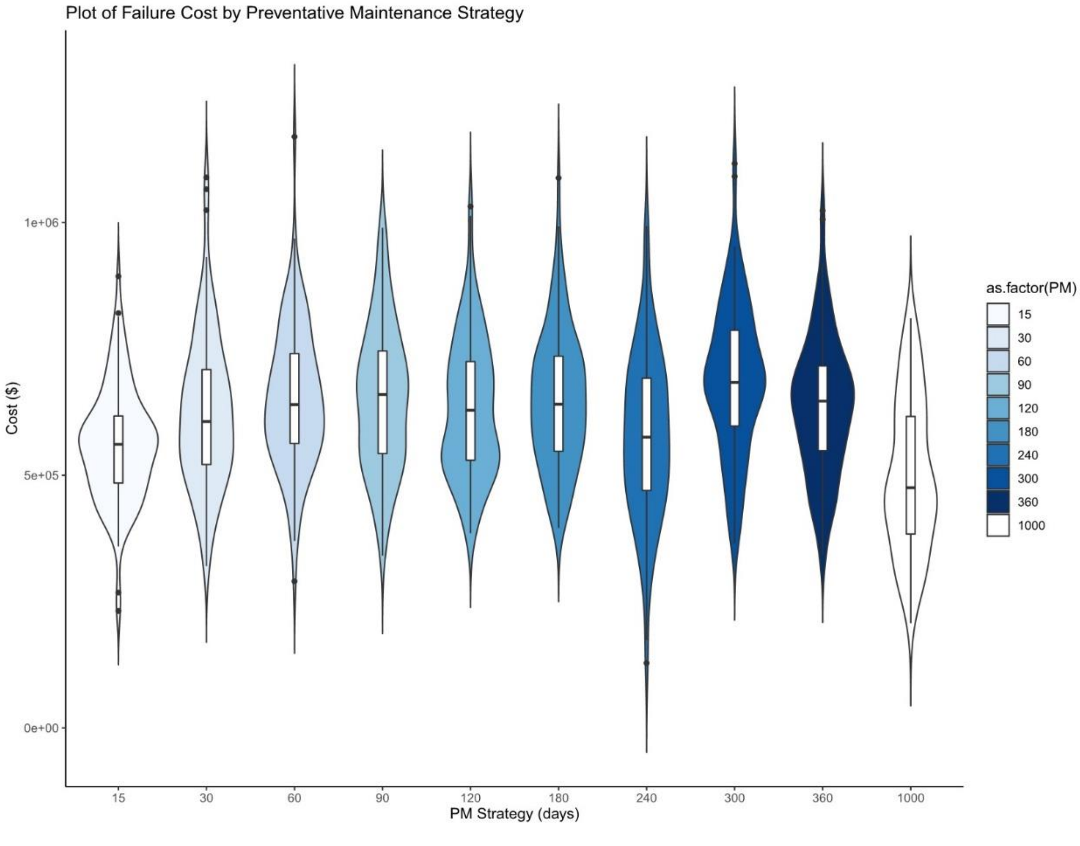


Figure 38: Low-cost preventive maintenance strategy influence on failure cost at Location 1.

4.3.1.1 Location 1 result analysis

After implementing the random forest decision tool, both sun hour and days from the last failure where the top determinants for future failures in location 1. Both Figures 35 and 37 show a negligible variation between high and low-cost preventive maintenance policies. That means failure modes have more influence on the system than the maintenance scenario. As described in the figures, a preventive maintenance strategy's duration has a negative correlation with both the failure and annual cost. Thus, as the duration for inspection increases, both failure, and annual costs decrease. Although this is not the most desirable result, the days from the last failure as a top determinant for failure modes explains this phenomenon. The days from last failure's interplay with weather influencers for a relatively large failure extent created some noise with the data as time increases. As a result, the corrective maintenance plan has proved to be the best optimal strategy at that location.

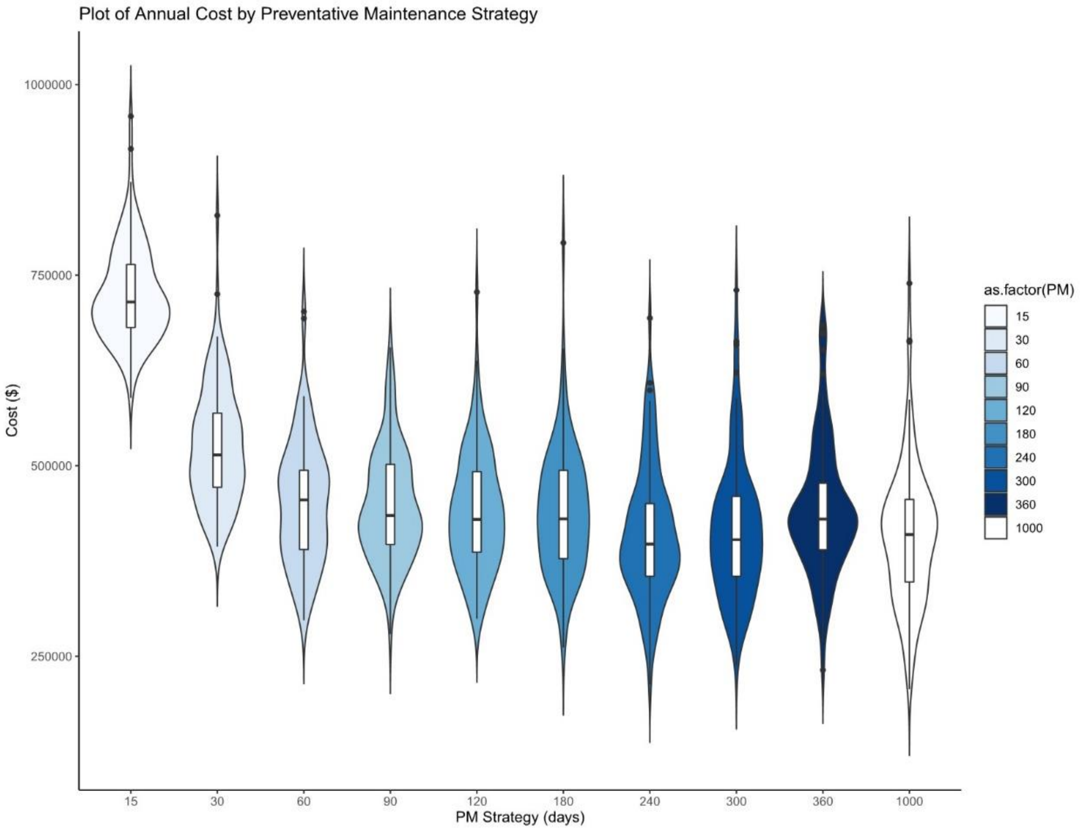


Figure 39: High-cost preventive maintenance strategy influence on annual cost at Location 2.

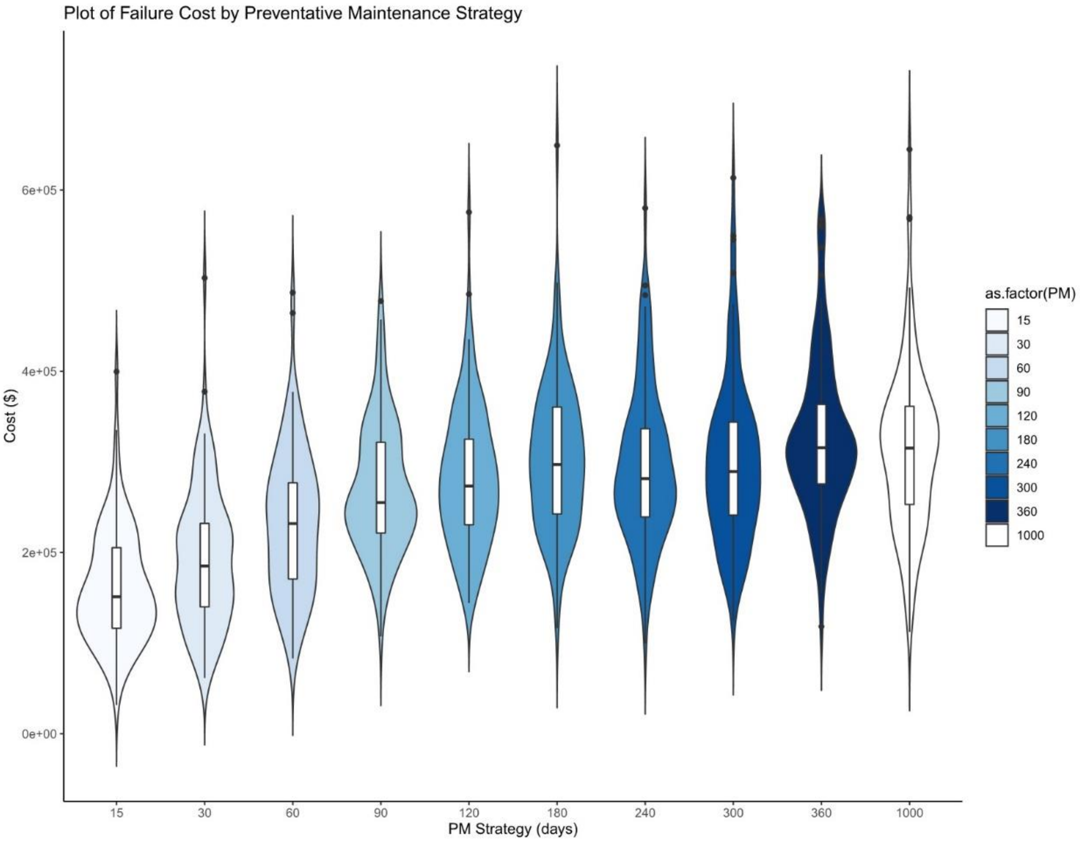


Figure 40: High-cost preventive maintenance strategy influence on failure cost at Location 2.

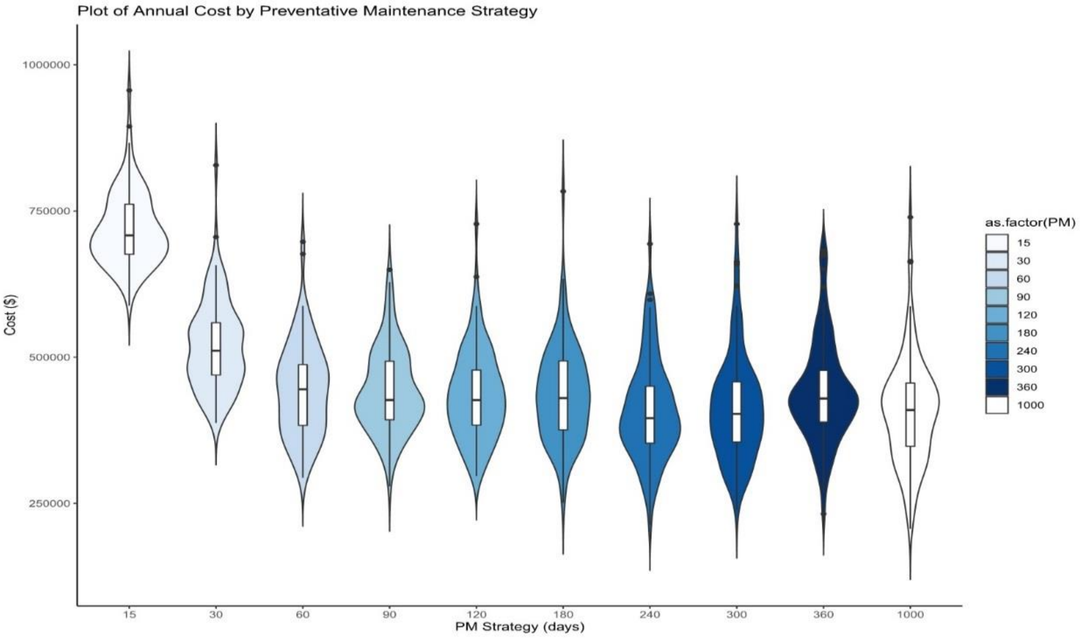


Figure 41: Low-cost preventive maintenance strategy influence on annual cost at Location 2.

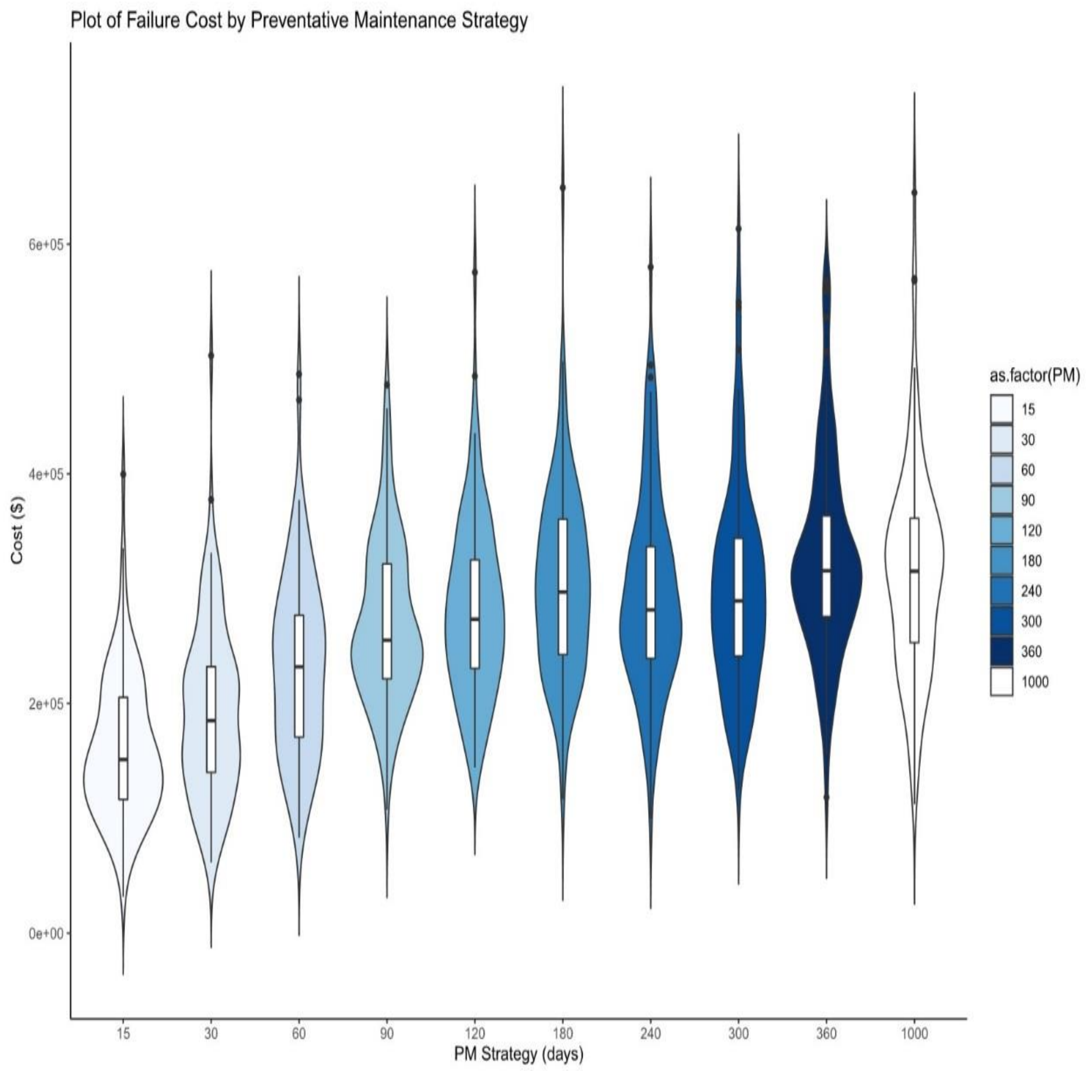


Figure 42: Low-cost preventive maintenance strategy influence on failure cost at Location 2.

4.3.1.2 Location 2 result analysis

Both locations 1 and 2, had very similar simulation outputs and specifications. They had very similar failure extents, relative sameness for high and low-cost preventive maintenance results, and similar failure modes. However, as shown in Figures 41 and 42, location 2 shows different results and the 240-day duration is the optimal maintenance strategy for prognostic approaches. It has a slightly lower average than its runner-up, the corrective maintenance. The only difference is that in location 2, the prominent influencers are humidity and wind speed, which are only weather influencers. Thus, days from the last failure, in this case, is one of the least determinants for failure. As a result, the duration had a positive correlation with failure cost, but a negative one with annual cost reaching the minimum at 240 days.

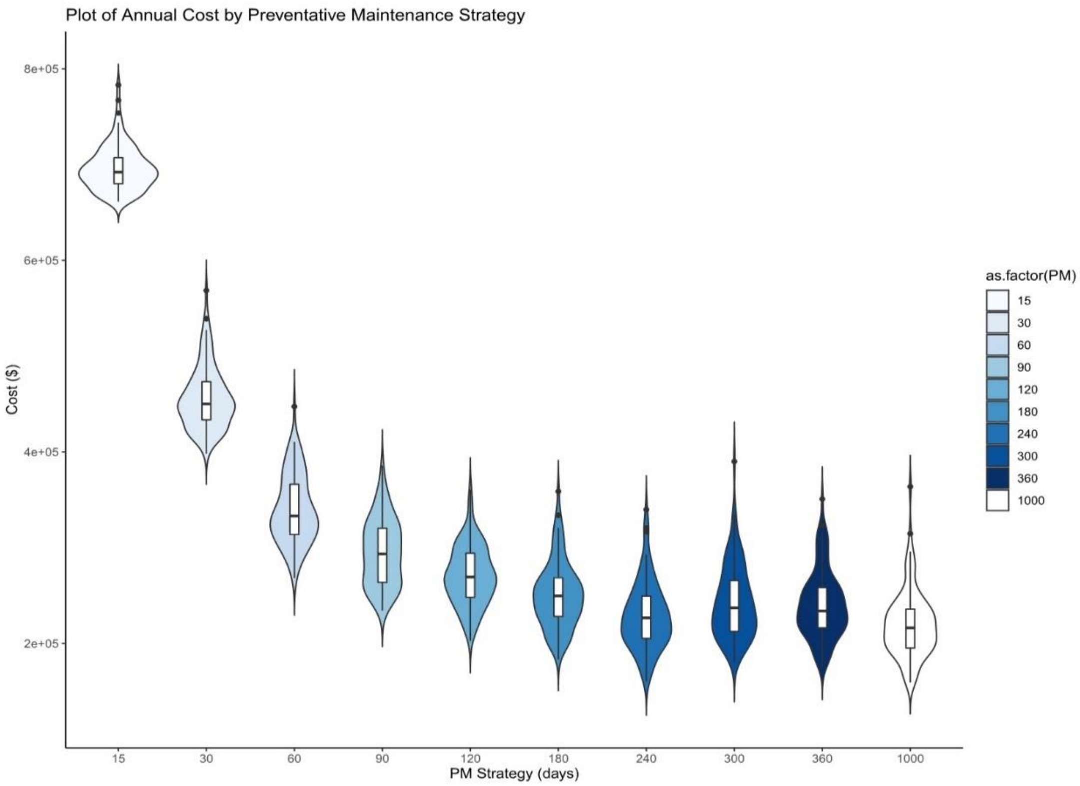


Figure 43: High-cost preventive maintenance strategy influence on annual cost at location 3.

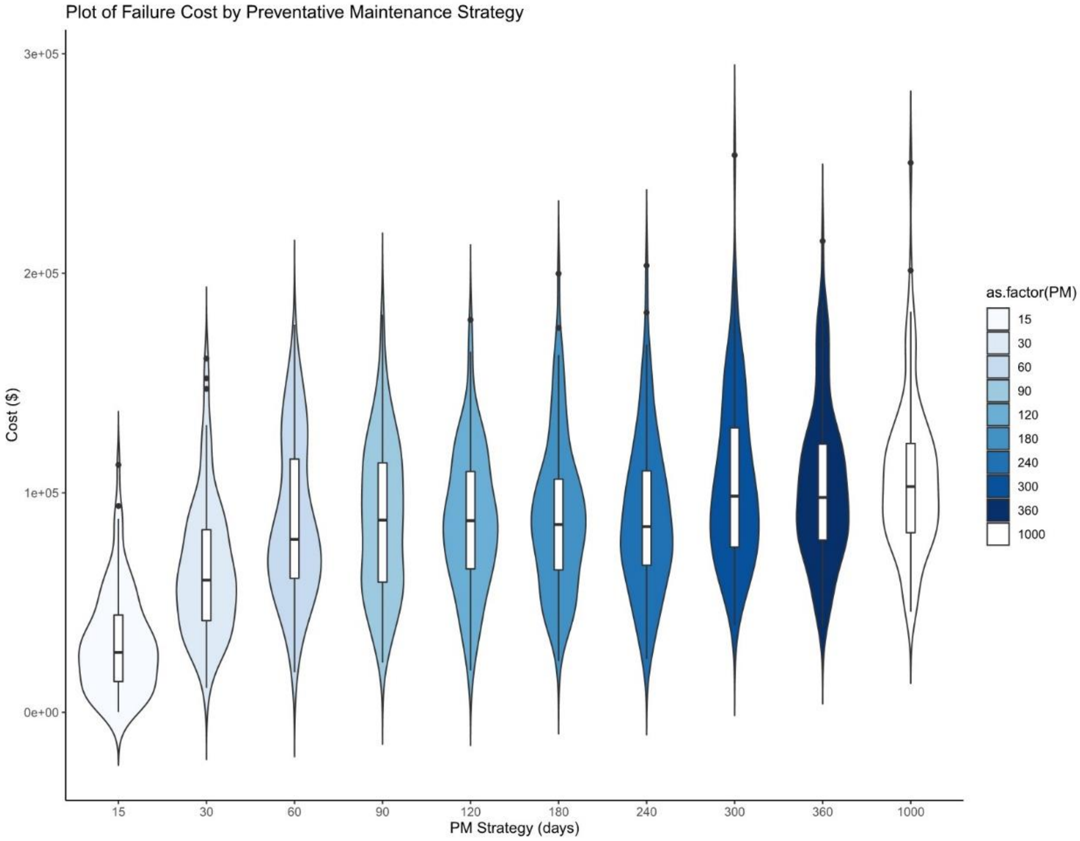


Figure 44: High-cost preventive maintenance strategy influence on failure cost at Location 3.

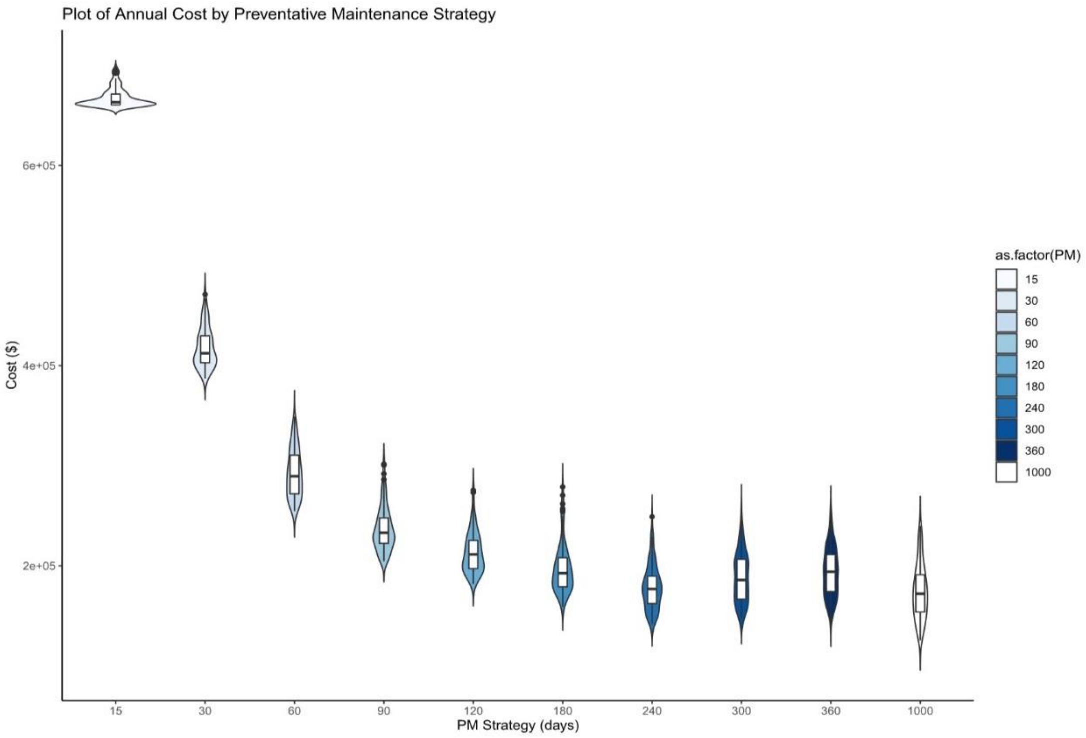


Figure 45: Low-cost preventive maintenance strategy influence on annual cost at Location 3.

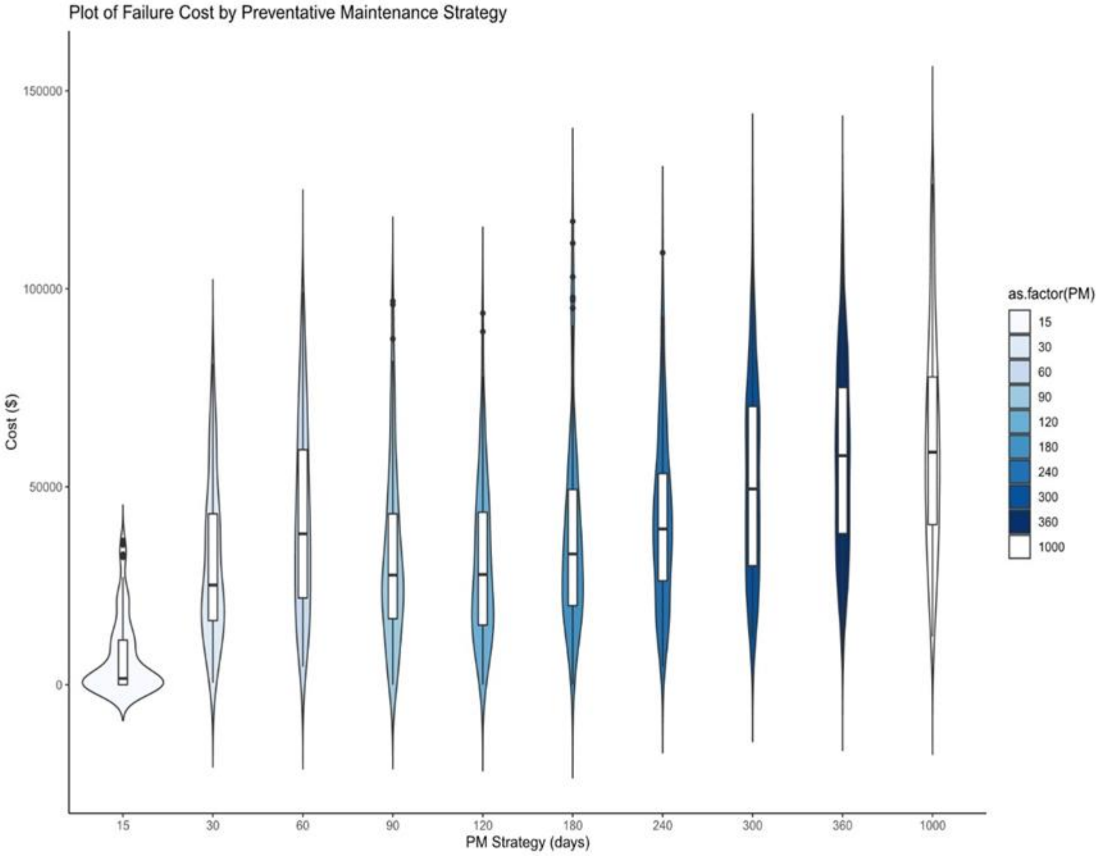


Figure 46: Low-cost preventive maintenance strategy influence on failure cost at Location 3.

4.3.1.3 Location 3 result analysis

Location 3 had different results compared to those of the prior locations. Its prominent influencers, like location 1, were humidity and days from the last failure. However, despite having similar determinants, failure modes at location 3 are considerably less than that of location 1. Thus, there extent and probability are less than those at location 1. In this case, the random forest did not affect the results as much as it did in location 1. This said, and as shown in figures 44 and 46, having low-cost preventive maintenance would severely affect the density of failure and annual cost at each interval. As a result, both the 240-day preventive maintenance and the corrective maintenance share similar results at location 3.

Based on these results, we see that both corrective maintenance and 240-day preventive maintenance policy have nearly equal influence on the system with failures determined by weather and days from the last failure. This result makes sense as the impact of weather outweighs the impact of repair in the form of days since the last fail for this asset. The models point to a maintenance strategy that is consistent with that of practice – inspect and repair before the rainy season and then implement a corrective strategy for the remainder of the year.

Chapter 5

Discussion and Conclusion

5.1 Discussion

The purpose of this study was to explore the effect of implementing several preventive maintenance strategies on failure and total maintenance cost. To achieve this purpose, a risk-based maintenance strategy was implemented on an EPDM waterproofing system at a prototype airport. The methodology tools helped simplify the model into four different categories for study: Location 1 sheet-based, Location 1 skirting, Location 2 sheet-based, Location 2 skirting, and Location 3 sheet-based. Random forest was built on past data in order to simulate the probability of failure taking external factors (such as weather) into consideration. Based on the simulation, it was found that when the weather has a large impact on the probability of failure for an asset, then a “weather-driven” maintenance policy and corrective maintenance perform comparably.

5.1.1 The optimal maintenance strategy

Among all preventive maintenance durations, a 240-day model has shown the best outcome for all locations. 240-day duration means an eight-month time lapse between a preventive task and the other. Since the simulation started on January 1, a preventive maintenance mode will be scheduled each year on September 1. Keeping in mind that waterproofing repair and maintenance is inevitably impossible during the winter season as exposed areas make maintenance difficult during the high precipitation months of winter. Providing preventive maintenance before the winter season is a good approach. Thus, rather than implementing an extended ineffective 360-day policy, the system suggested the 240-day duration as the best preventive maintenance strategy associated with low annual costs compared to other strategies. In summary, the 240-day maintenance scheduling appears to balance the days from last failure and weather effects on the system. However, as shown in the above figures, a 240-day maintenance strategy is not necessarily optimal for all locations.

5.2 Conclusion, Limitations, and Future Works

5.2.1 Conclusion

Waterproofing is one of the most complex structural assets. A leakage failure might be present in an area distant from the main defect source. Many engineers find managing leakage to be a complicated task. To make things worse, leakage in a public facility, especially airports, can result in greater consequences. Airports and public facilities hold a generalized picture of the country. Thus, very high quality and safety standards are present in these locations all over the world.

A risk-based multi-objective maintenance strategy provides profound solutions to problems associated with high maintenance costs, excessive failure modes, and damaging consequences in complex environments. This thesis served to disentangle some of the complexity associated with the maintenance of waterproofing by integrating weather-related and time-related predictors of failure in a simulation of multiple preventive maintenance strategies. The outcome of the simulation allows for the selection of the optimal, risk-minimizing, multi-objective maintenance strategy.

Results showed that the 240-day duration with low-cost preventive maintenance had a very similar effect to that of a solely corrective maintenance strategy.

5.2.2 Limitations

There are several limitations in this study that affect the dissertation’s realism.

1) The inexistence of proper data for mining that would have provided real insights on the frequency and effect of root causes, the occurrence of past repair modes, and the actual cost of consequences for each failure. Thus, limiting this thesis to only two root causes for future failures. Moreover, a multi-condition rating should be appropriately implemented to give more precision to repair cost levels in the simulation.

2) Applying an overhaul and new waterproofing applications are excluded from the study. Thus, limiting it to only failure modes and variation.

3) Due to the lack of data, only two maintenance strategies were tested (low and high-cost preventive maintenance). Applying multi-cost preventive maintenance

would provide more insight into the relative risk of each preventive maintenance strategy.

4) This is just a theoretical approach to the waterproofing system. An on-site application might provide different results.

5) Indirect consequences can withstand several other elements like competition, penalty, condition, etc.

5.2.3 Future Works

Several future works can be provided as extensions to this thesis. For example, by adequately scheduling inspection activities, the cost of inspection and thus the cost of the preventive maintenance strategies can be reduced.

It would also be interesting to see if similar results are obtained when simulating maintenance policies for other assets with a high failure dependency on external factors such as weather – and in contrast assets with only intrinsic (wear and tear) sources of failure. One would expect that when external factors impact failure so strongly, then corrective maintenance becomes more attractive. Testing this hypothesis requires the addition of multiple assets to this study.

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