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The Consequences of Deferring Taxiway and Runway Maintenance at Amsterdam Airport Schiphol

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Executive Summary

Amsterdam Airport Schiphol is a hub in a global network that resides in the vicinity of Amsterdam. In the status quo, approximately 500 thousand aircraft movements are annually welcomed. However, it is anticipated that the number of operations will further proliferate in the foreseeable future and hence, the taxiway and runway asphalt pavements will have to endure higher load repetitions. In combination with oxidation, precipitation and ultraviolet radiation, the asphalt properties will alter and lead to accelerated deterioration. This inherently provokes durability issues and the asphalt pavement will become more susceptible and less robust to climatic and traffic loading. To guarantee the structural and functional integrity of the taxiway and runway pavements, Schiphol appointed Heijmans as the main contractor for Parcel one. The responsibility of the latter is to conceive a tailor-made maintenance plan to maintain the pavement. The current accumulated pavement area of Parcel one is 400 hectares, for such a vast acreage the annual allocated maintenance budget is over tens of millions of euros. However, as financial resources are finite, not all project can be effectively deployed. A recent example are the travel restrictions during the pandemic earlier this year, that led to unprecedented (adverse) repercussions for Schiphol. The magnitude of consequences was tremendous as 400 million euros of losses were anticipated for solely 2020. Thereupon, as a response to alleviate the deficits, the airport introduced measures to curtail financial expenditures, which among others led to several revoked and deferred maintenance projects. In the end, deferring maintenance is a tempting decision because the consequences are implicit and not immediately emerging. And since these situations are often inevitable, it is pivotal to understand its consequences to prematurely prioritize the pavement maintenance projects, to indicate which projects may not be deferred. Therefore in this exploratory research, endeavors have firstly been devoted to qualitatively investigate the rationales that underpin these nontrivial decisions, beside the limited financial resources. Through a set of interviews with pertinent stakeholders, it was found that new development projects and operational restrictions are often the culprits. After familiarization with why maintenance projects are deferred, pavement failures were scrutinized in the light of deferred maintenance. Through aircraft transponder data and other data sources, the circumstances, under which the pavement failures tend to emerge, were investigated with the Cox proportional-hazards model. This in-depth quantitative analysis exhibited that pavement failures are indeed more likely to manifest on older pavement sections, which demonstrates that deferring maintenance is inextricably intertwined with the emergence of more pavement failures. For example, 12-year-old pavement sections have a 50% higher chance to incur a pavement failure, compared to 8-year-old sections. In addition, it was found that pavements failures would develop more frequently in the bay areas and near junctions. Also pavement sections that are subject to aircraft with moderate taxi speeds or high traffic intensity, appear to deteriorate quicker. Thereupon, the operational impact of pavement failures was analyzed. It was found that a pavement failure at certain pavement sections, could result in traffic detour costing up to €90,000 a day. Ultimately, all of these insights were processed into a time-dependent choropleth model, that depicts the chance on a pavement failure per pavement section. It is envisaged that this elaborate model could support decision-makers in making substantiated and rational decisions in the prioritization of maintenance projects, to guarantee that the most critical projects are identified and subsequently materialized.

Managementsamenvatting

Amsterdam Airport Schiphol is de internationale hub van Nederland en bevindt zich nabij Amsterdam. Momenteel verwelkomt Schiphol zo'n 500.000 vluchten op jaarbasis, echter is de verwachting dat dit aantal geleidelijk door gaat groeien. Hierdoor krijgt het asfalt van de taxi- en landingsbanen meer te voorduren in de toekomst. Deze blootstelling aan de toenemende verkeersbelasting, in combinatie met oxidatie, Uv-straling en andere weersomstandigheden, bevordert het verouderingsproces van het asfalt. In de loop der jaren zullen de fysische en mechanische eigenschappen van het asfalt niet meer voldoen aan het gewenste niveau. Om te waarborgen dat het asfalt zijn functie kan blijven vervullen is onderhoud nodig, mede hierdoor is Heijmans door Schiphol aangewezen als de hoofdaannemer voor Perceel één. Dit areaal omvat 400 hectare aan asfaltbekleding en bestaat onder meer uit de landingsbanen, taxibanen en de baaien. De jaarlijkse onderhoudsramingen voor dit terrein bedragen tientallen miljoenen euro's. De ervaring leert dat financiële tegenslagen een significante impact kunnen hebben op de beoogde onderhoudsprojecten, met als gevolg dat projecten worden uitgesteld. Een recentelijk voorbeeld zijn de verregaande reisbeperkingen die afgekondigd werden als gevolg van de coronapandemie. Hierdoor is de luchtvaartsector disproportioneel hard geraakt, ook luchthaven Schiphol is hier niet ongeschonden uitgekomen. De gevolgen zijn desastreus en een verlies van €400 miljoen wordt voor 2020 verwacht. Om de financiële tegenvallers op korte termijn de kop in te drukken, worden onderhoudsprojecten verzet. Hoewel het verzetten van onderhoud een aanlokkelijke keuze is, gaat het mogelijk gepaard met negatieve repercussies. Om de langlopende discussies over dit onderwerp te beslechten en om de onderhoudsprojecten te kunnen prioriteren, is het van essentie om de consequenties van het verzetten van taxi- en landingsbaan onderhoud op Schiphol te kwantificeren en met name de consequenties voor het storingsgedrag van het asfalt. Dit explorerend onderzoek tracht deze lacune in de literatuur op te vullen door ten eerste de achterliggende redenen voor het verzetten van asfaltonderhoud te identificeren middels interviews met relevante stakeholders. Vervolgens zijn de asfaltstoringen, die zich in de afgelopen jaren hebben voorgedaan, samen met de omstandigheden waarin zij ontstaan zijn, onderzocht met het statistische Cox proportional-hazards model. De parameters die gebruikt zijn, betreffen het aantal vliegbewegingen, de snelheid waarmee ze zich voortbewegen, de leeftijd van het asfalt, de staat van de fundering en het type wegvak. De bevindingen van de kwantitatieve analyse laten een correlatie zien tussen asfaltstoringen en de leeftijd van het wegdek. Dit impliceert dat onderhoudsverschuivingen verweven zijn met een hogere storingskans. Om precies te zijn, een asfaltlaag van twaalf jaar oud heeft 50% meer kans op een storing dan een asfaltlaag van acht jaar oud. Het onderzoek heeft tevens aangetoond dat storingen vaker ontwikkelen bij de baaien en kruisingen. Ook lijken asfalt lagen die onderworpen worden aan langzame vliegtuigen en/of veel verkeersbelasting dit gedrag te vertonen. Als vervolg op de storingsanalyse, is de operationele impact van storingen in kaart gebracht door middel van een graaf netwerk dat het bestaande rijbanenstelsel van Schiphol simuleert. De graaf bestaat uit knopen die verbonden zijn met lijnen. Door een afstands- en snelheidsattribuut toe te voegen aan de lijnen, kunnen de omrijdtijden, als gevolg van een storing, eenvoudig berekend worden. Deze zijn vervolgens gekoppeld aan de vertragingskosten uitgedrukt in minuten en het aantal vliegtuigen dat overlast hiervan ondervindt. Deze operationele analyse laat zien dat de omrijdkosten voor sommige secties op kunnen lopen tot €90,000 per dag. De verkregen inzichten zijn vervolgens gebundeld in een dynamische choropleth, die de kans op asfaltstoringen weergeeft per wegdeksectie. Het visuele model weergeeft de numerieke waardes in de vorm van kleuren en toont hoe dit door de tijd heen veranderd. Dit model dient besluitvormers van zowel Heijmans als Schiphol te ondersteunen in het maken van rationele keuzes en afwegingen voor onderhoudsprojecten.

Acknowledgements

The past six months have been a tremendous journey with many ups and down. Nonetheless, through perseverance and effective guidance from my supervisors this chapter was concluded successfully. They provided me the space to shape my own research and gave me positive incentives when deemed necessary. Therefore I would like to take this opportunity to thank Ir. John Visée and Ir. Patrick van Beers, on behalf of Heijmans, and Dr. Andreas Hartmann and Drs. Johan Boes, on behalf of the University of Twente, for their guidance. In addition, I would like to express my gratitude and appreciation to my Heijmans colleagues that took the effort, without any hesitation, to explain things and to guarantee the availability of information and data.

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J.K. Au Yeung
欧阳家希

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List of Abbreviations

04-22	Oostbaan
06-24	Kaagbaan
09-27	Buitenveldertbaan
18L-36R	Aalsmeerbaan
18C-36C	Zwanenburgbaan
18R-36L	Polderbaan
ADSB	**A**utomatic **D**ependent **S**urveillance **B**roadcast
ASK	**A**nti**sk**id
ASM	**As**set **M**anagement
BLR	**B**inary **L**ogistic **R**egression
CAP	**Ca**pital **P**rogramme
CapEx	**Cap**ital **Ex**penditure
CBS	**C**entraal **B**ureau voor de **S**tatistiek
FAA	**F**ederal **A**viation **A**dministration
FOD	**F**oreign **O**bject **D**ebris
GIS	**G**eographic **I**nformation **S**ystem
GOH	**G**root **O**nder**h**oud
GPS	**G**lobal **P**ositioning **S**ystem
ICAO	**I**nternational **C**ivil **A**viation **O**rganization
IQR	**I**nter**quartile** **R**ange
KLM	**K**oninklijke **L**uchtvaart **M**aatschappij
LVNL	**L**ucht**v**erkeersleiding **N**eder**l**and
MJOP	**M**eer**j**aren **O**nderhouds**p**lan
MTOW	**M**aximum **T**ake **O**ff **W**eight
OJP	**O**nderhoud **J**aar **P**lan
OLS	**O**rdinary **L**east **S**quare
OpEx	**Op**erating **Ex**penditure
OPS	**Op**eration**s**
PCI	**P**avement **C**ondition **I**ndex
PH	**P**roportional **H**azards
PFAS	**P**oly- and **F**luor**a**lkyl **S**toffen
PLuS	**P**rojectmanagement **Lu**chthaven **S**chiphol
SAP	**S**ystems **A**pplications and **P**roducts
TDZ	**T**ouch**d**own **Z**one
TOC	**T**otal **C**ost of **O**wnership
UAC	**U**niform **A**dministrative **C**onditions
WAP	**W**orks **A**sset and **P**lanning

Glossary

Airside: — *"The movement area of an airport, adjacent terrain and buildings or portions thereof, access to which is controlled."*

Apron: — *"A defined area, on a land aerodrome, intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fueling parking or maintenance."*

Displaced Threshold: — *"A threshold not located at the extremity of a runway."*

Holding Bay: — *"A defined area where aircraft can be held, or bypassed, to facilitate efficient surface movement of aircraft."*

Meerjaren Onderhoudsplan — *"A maintenance plan that stipulates the expected maintenance activities for the forthcoming five years. In this context, it entails all the maintenance activities on the pavement assets of Parcel one that have a greater life expectancy than three years."*

Parcel One: — *"Parcel one includes all infrastructure and facilities on and surrounding the runways, including taxiways, bays, service roads, signs and lighting. Thus, aprons and terminals are not part of Parcel one."*

Runway: — *"A defined rectangular area on a land aerodrome prepared for the landing and take-off of aircraft."*

Taxiway: — *"A defined path on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another."*

Touchdown Zone: — *"The portion of a runway, beyond the threshold, where it is intended landing aeroplanes first contact the runway."*

Chapter 1

Introduction

1.1 Background

Heijmans is a listed contractor located in the Netherlands and is active in the realm of infrastructure, utilities and housing development. Pertaining to the former, Heijmans has hitherto nine years of experience with conducting infrastructure related maintenance at Amsterdam Airport Schiphol (informally known as Schiphol Airport). In 2019 Heijmans signed the performance-based contract for the Schiphol runway sites parcel, which entails an indicative annual turnover of approximately €47 million. This contract has signified an alteration in the relationship between Heijmans and Schiphol, as a pronounced shift in responsibility has taken place. As Schiphol puts it: "Schiphol determines the what and the main contractor is the expert on the how."

As the main contractor for Parcel one, Heijmans is responsible for all infrastructure and provisions on and surrounding the runways, including taxiways, holding bays, service roads, signage and lighting. Fig. 1.1 depicts the entire acreage of Parcel one and the names of assets that will be repeatedly mentioned in the forthcoming chapters. Furthermore, in the remainder of this research, a number of aviation related jargon will be used. To ensure consistency, this research will adhere to the definitions provided by the International Civil Aviation Organization (ICAO) [1].

1.2 Schiphol Airport Pavement Maintenance

Taxiway and runway pavements have to endure a tremendous amount of repetitive traffic loading's, imposed by heavy aircraft that may weigh hundreds of tons. Traffic loading in combination with oxidation, precipitation and ultraviolet radiation, cause embrittlement in the pavement properties and lead to gradual deterioration of the pavement [2]. This will provoke durability issues and makes the pavement more susceptible to climatic and traffic loading. Ultimately, maintenance will be required to maintain the functional and structural integrity of the pavement at or above the desired standards [3]. For instance, each of the six runways at Schiphol are annually closed for approximately a week, allowing maintenance engineers to assess the quality of the pavement, and if necessary, maintenance will be conducted. However, if certain activities cannot be administered within the given time frame, functional repair may take place to temporarily nullify the repercussions of the particular defect, in order to be repaired at a more adequate moment.

In addition, planned large maintenance, that may require several weeks, will be performed on one runway per year, at a frequency of approximately once per seven years. This entails activities such as rehabilitation or replacement of certain pavement areas to enhance pavement longevity. Furthermore, when pavement failures emerge, unscheduled maintenance has to take place to rectify it. If the failure is nontrivial and can potentially impair the airport operations, it will immediately be rectified to alleviate the risks. However, if the urgency is less alarming, functional repair may be procrastinated until next periodic maintenance.

Regarding planned maintenance, Heijmans is obliged to present a maintenance planning for the subsequent five years to Schiphol. This maintenance/budget planning is stipulated in the Meerjaren Onderhoudsplan (MJOP). It encompasses all the anticipated asset replacements that have a greater life expectancy than three years and shows the corresponding details, such as estimated costs and duration's. Schiphol will examine the proposed MJOP and either accept the planning or request for alterations. After the revisions to the initial MJOP, the definitive MJOP with an elaborate cost scheme will be presented to Schiphol again. Upon approval, the MJOP plans will be materialized by Heijmans.

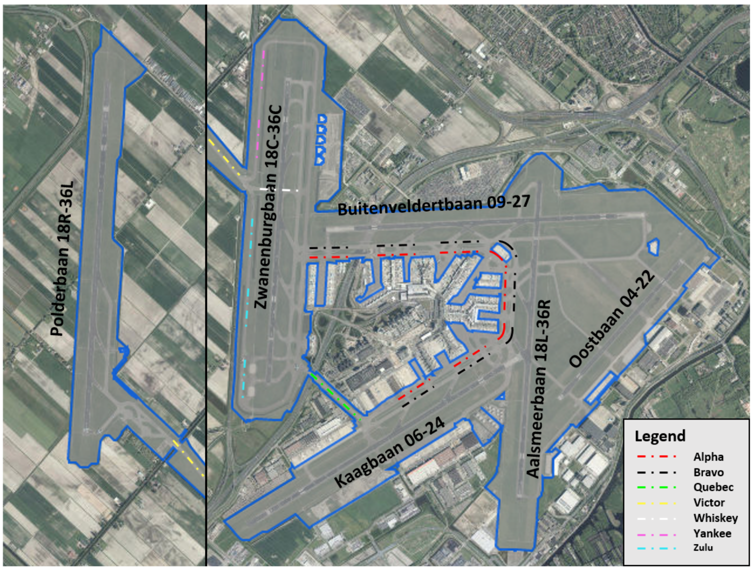


Fig. 1.1. Schiphol Airport Parcel one.

1.3 Research Problem and Objectives

Now the scope of activities for Heijmans and the necessary details have been explained, it is time to introduce the research problem, which is also the main reason why this research is pursued. However, since research typically commences with a problem that is ill defined in the earlier stages, it is of essence to firstly narrow down the problem to obtain a demarcated and researchable topic [4]. Hence, in the subsequent sections, a cause and effect diagram will be presented to provide contextual details about the nature of the research problem. Consequently, this will lead to a problem statement and the corresponding research objectives and questions.

1.3.1 Nature of the Research Problem

Through a cause and effect diagram, the research problem and its emergence will be enlarged. In essence, the focal node of the diagram in Fig. 1.2, is Schiphol that defers taxiway and runway pavement maintenance, which may have dire repercussions, as exhibited in the diagram. Among others, it can have a knock-on effect and may impinge on the airport operations, under the assumption that pavement deterioration persists and increases the likelihood of pavement failures. These failures are, depending on the urgency, remedied during unplanned maintenance. This can lead to temporary closure of a taxiway or runway, resulting in traffic detours, additional taxi time and extra operational costs for airlines. These additional costs may result in deduction of airport fees that airlines pay, leading to lower revenue streams for Schiphol. This showcases that deferring maintenance may be intertwined with unfavorable effects for different stakeholders.

On the other hand, since Heijmans has a performance-based contract with Schiphol, the former must adhere to a predefined set of objectives and indicators pertaining to asset performance. These objectives and indicators are stipulated in the internal "Verification-matrix Maintenance Parcel 1" document. For example, it dictates that failures must be rectified within eight hours after announcement. Failing to meet these objectives and indicators can result in penalties for Heijmans. Especially when failures are correlated to maintenance deferment, it may become a nuisance for Heijmans. Therefore, deferring taxiway and runway pavement maintenance is also unpleasant from the perspective of Heijmans.

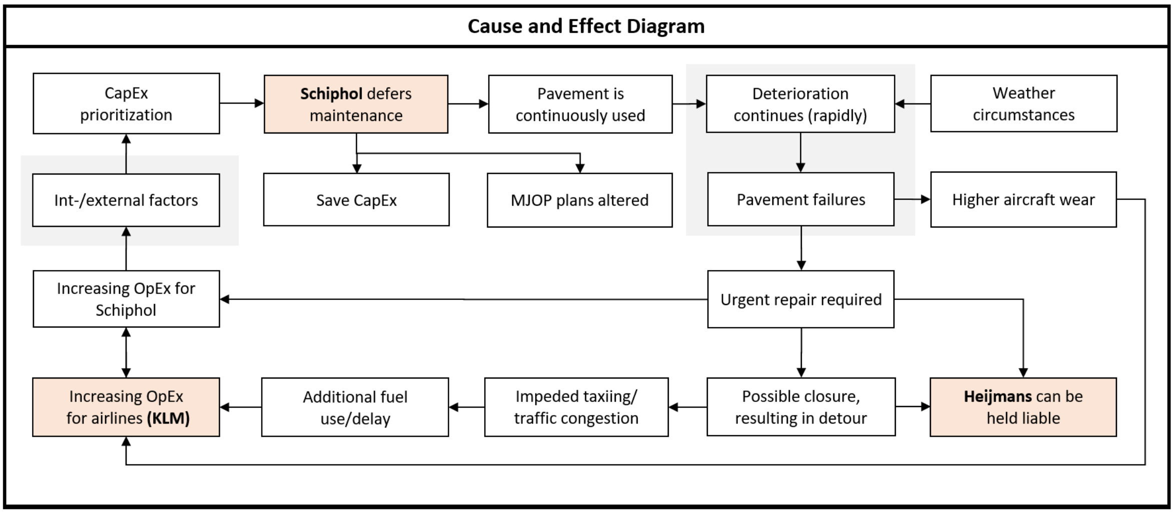


Fig. 1.2. Problem Structuring with Cause and Effect Diagram.

1.3.2 Problem Statement

The cause and effect diagram highlighted two "grey" areas that are of particular interest for this research. The first area entails internal and external factors that lead to the problem in the first place. Conceivably, these factors are inevitable and will compel Schiphol to defer pavement maintenance. For example, during a financial downturn, deferring pavement maintenance is the quickest course of action to temporarily reduce the budget deficits. Thus this recurrent problem will always persist, therefore the notion is not to bypass nor to negate this delicate problem, but to thoroughly comprehend this phenomenon to seek an appropriate approach to work with this issue in the future. In this context, the "appropriate approach" is understood as the prioritization of the maintenance projects, to tackle the most vital pavement sections. This introduces the second area, which describes a knowledge gap, because developing a tailored approach is only feasible when the consequences of deferred pavement maintenance for the pavement itself are well understood. Currently, it is thought that maintenance deferment may lead to nontrivial consequences for the pavement, however they are still insufficiently understood. Existing scientific literature has hardly touched upon the consequences of deferring taxiway and runway pavement maintenance, let alone quantifying the consequences. This makes exploring this topic all the more important, because it will render the pavement maintenance prioritization process for Schiphol better substantiated and underpinned by facts. And because Heijmans is the main contractor of the pavement assets, has the in-house pavement expertise and possesses the majority of the pertinent data, Schiphol has asked Heijmans to inquire into this topic to provide extensive insights.

"

To be concise, the defined problem statement is as follows: Internal and external factors compel Amsterdam Airport Schiphol to occasionally defer taxiway and runway pavement maintenance. However, the associated consequences and most notably, the effect on pavement failures, are implicit and intricate to quantify. This knowledge gap stresses the necessity to investigate this issue, to ultimately aid decision makers in making rational and well substantiated maintenance related decisions.

"

After the familiarization with the contextual details about the nature of the problem and the research problem, the research objectives and questions of this research were defined. The former clarifies why this research is being conducted, whereas the latter serves as a guide to structure the process of collecting and analyzing information to attain the objective [4]. The formulated research objective and the corresponding research questions are depicted in Fig. 1.3.

Research Objectives

Research Objectives

The purpose of this study is twofold. 1) First of all, to identify the rationales for deferring taxiway and runway pavement maintenance at Amsterdam Airport Schiphol.

2) and secondly, to investigate the consequences of deferring taxiway and runway pavement maintenance for the risk of pavement failures, to support the maintenance project prioritization process for decision makers of Amsterdam Airport Schiphol and Heijmans.

Research Questions

1. Which pertinent factors are decisive in the decision to defer taxiway and runway pavement maintenance?
2. How often is taxiway and runway pavement maintenance deferred by Schiphol and for how long?
3. Is deferred taxiway and runway pavement maintenance related to an increase in pavement failures, and if so, to what extent?
4. How do other parameters, in consolidation with deferred pavement maintenance, intensify the occurrence of pavement failures?
5. How does a pavement failure affect the airport operation of Schiphol Airport?
6. How can the consequences of deferred taxiway and runway pavement maintenance be exhibited in an easily perceivable dynamic environment to support decision makers in the maintenance project prioritization process?

Fig. 1.3. Research Objective and Research Questions.

1.4 Research Methods

The nature of the research problem was explained in the problem statement, which led to the formulation of the research objectives and questions. This section will now proceed with the research boundaries and the research methodology. The former intends to limit the scope of the investigation to a specified area to ensure that this research can be conducted within a reasonable amount of time. The latter on the other hand, elaborates on the research methods that will be deployed to respond to the set of research questions.

1.4.1 Research Viability and Boundaries

To obtain a viable research that is balanced in terms of relevance and feasibility, the research scope must be defined. In addition, this will give an accurate impression of what this research will involve and more importantly what is omitted. The scope of this research entails the following:

- The spatial scope is limited to the runways, taxiways and bays of Parcel one, that are utilized by aircraft. This implies that regular roads or electrical systems at Parcel one are not part of the scope.
- This research will only focus on the functional characteristics of the taxiway and runway pavements (i.e. the asphalt layer). This is because maintenance to enhance the structural characteristics (i.e. the pavement foundation) of pavement occurs seldom, due to its greater longevity.
- Only the consequences of large planned maintenance in the MJOP will be considered. Hence, smaller annual maintenance, as stipulated in the Onderhoud Jaar Plan (OJP) are omitted. A reason for this decision is that small maintenance is only shortly postponed, which makes the consequences hardly detectable, if not undetectable.
- The consequences for the pavement, in terms of pavement failures will be considered in this research. Degradation of the pavement is not directly considered, due to insufficient data availability. As will be mentioned in the literature study, images of the pavement are captured during pavement inspections to determine the current state. By comparing pictures of distresses and how they evolve overtime, it can be inferred how the size and severity of the distresses develop as time passes. However, since the inspections take place annually and the distresses are remedied in shorter time intervals, it is impossible to draw any conclusions about how distresses and pavement degradation evolve over time.
- The primary focus of this research is put on the consequences for the taxiway and runway pavement. Nonetheless, operational consequences such as delay and extra fuel use will be

considered in this research. Consequences such as additional pollution, noise or aircraft wear are not, since this will drastically enlarge the research scope.

- As mentioned before, Schiphol is ultimately the entity that determines the "what", whereas Heijmans is responsible for the "how" in the Schiphol maintenance decision-making. Hence, the former has the authority to waive the provided advice. Evidently, this may affect the position of Heijmans, and most notably the Parcel one performance-based contract. However, since the primary objective is to investigate the consequences of deferring taxiway and runway pavement maintenance in general and not to specifically investigate the repercussions of Schiphol's decisions for Heijmans, this topic will not be addressed in this research.

1.4.2 Research Design

This section intends to explain the research methods and software that will be deployed to respond to the research objective and questions. To keep a clear overview, the conceptual research design in Fig. 1.4 has been segregated into three main components, namely the introduction/problem statement, body of the report and finally the conclusions and recommendations. Evidently, the former is the backbone of the research, thus a feedback loop is connected to this, to ensure that this research is heading into the right direction. Finally, the body of the report is further decomposed into four respective phases, each phase elaborates on a different topic.

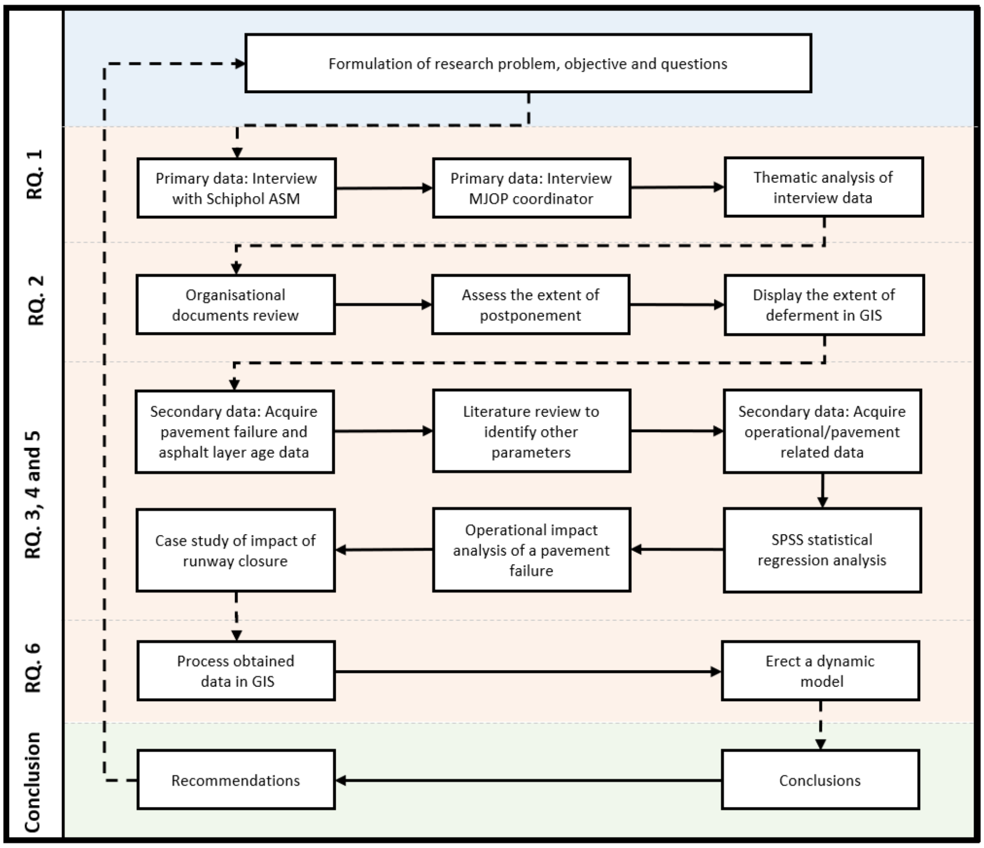


Fig. 1.4. Conceptual Research Design.

Phase One

As one can see, this research will commence with the deployment of qualitative data collection methods to better understand why maintenance is actually deferred. It is deliberately chosen to use interviews, as the corresponding question is qualitative in nature and extensive responses are required from a small number of experts, thus questionnaires or surveys are inferior to interviews in this case.

The notion is to use purposive sampling to select candidates for the interviews. Therefore, a Reliability Engineer, Civil Engineering Specialist and a Strategic Plan Developer have been selected from the Asset Management (ASM) team, which are closely involved in the MJOP conception and have the authority to defer taxiway and runway maintenance. In addition, as Heijmans plays a prominent role in conceiving the MJOP and is also the entity that is responsible for the implementation phase, a fourth interview will be held with a Heijmans insider. This helps to capture a complete narrative, as seen from different angles. Ultimately, the qualitative information from the interviews, will be transcribed, coded and the results will be elaborated accordingly (thematic analysis). The latter includes an overview of all the causes of maintenance deferment, underpinned with a stakeholder analysis that sheds light on the different internal and external parties and their degree of power to influence.

Phase Two

To respond to the second research question, organizational records like the MJOP will be examined, these documents should provide insights into all the pavement deferments and their extent. This scattered data should be, after acquisition, visualized to clearly show where and when maintenance has been deferred. This will later on, ease the data analyzing process. The notion is to highlight the locations where maintenance has been deferred and when. Presumably, this will be performed in Geographical Information System (GIS) or a similar software package. The preceding phase and this phase will emphasize on acquiring more contextual details about how the MJOP maintenance plans are conceived in the first place and why some of these plans are postponed. This is essential to investigate, as this research would not have been initiated without the reasons to defer pavement maintenance. Then regarding the extent of deferment, it will be analyzed because the magnitude of consequences depends on the extent of deferment. Only by fully understanding the latter, the consequences of deferring pavement maintenance can be investigated.

Phase Three

Investigating the consequences of deferring taxiway and runway pavement maintenance is cumbersome due to data restrictions. In the ideal case, the continuous indicator PCI will be used. However, as mentioned before, this is currently not recorded by Heijmans and hence hampers the feasibility of analyzing how the PCI develops as time passes. A suitable alternative is to investigate how pavement failures emerge and how time contributes herein. To explore whether a relationship exists between deferring pavement maintenance and pavement failures, all the failures that were reported by Schiphol must be enumerated. A proprietary database that qualitatively indicates the location of the failures is available for this purpose. To enhance the accuracy of the location, additional documents, such as work orders or images can be used, to better pinpoint the location.

Eventually, the pavement failures will be analyzed through a statistical regression model in SPSS, the Cox PH model. This model is versatile as it allows censored or incomplete data, which is often an issue with analyzing pavement related data, making regular regression models not suitable. In addition, this model allows the evaluation of the effects of other influential factors. Ultimately, this model will be used to address the objective, by analyzing the asphalt layer age of the particular section, at the time when the pavement failure occurred. Understanding how time affects the chance on a pavement failure, will also show what happens when a pavement maintenance is deferred. Additionally, beside the time variable, other parameters can be investigated that might contribute to the development of pavement failures in combination with deferred maintenance (e.g. details about the pavement foundation or the airport operation). To identify other parameters, a literature review will be conducted to scrutinize pertinent literature. If a parameter has significant meaning and can be incorporated in the analysis, with respect to data availability, it will considered in the statistical analysis. Most likely, the proprietary data will require some sort of preprocessing or manipulation, which will be done with Python or Excel.

After getting acquainted with the circumstances under which pavement failure tend to emerge, the operational impact of a pavement failure will be analyzed. The quantification of the operational impact for taxiways will be realized by computing the detour costs. For this reason, a taxiway network will be erected in GIS. On the other hand, runways are more intricate and cannot be assessed through traffic detour. However, in the past, the Polderbaan was closed due to a pavement failure in 2018. Therefore, a case study of this event will be conducted. This strategy allows the investigation of this phenomena in the real-life context.

Phase Four

In the concluding phase of the main body of the report, the gathered insights from the preceding chapters, will be consolidated into a single model. This model should address the risk of pavement failures and show how it alters in time, to reflect how deferring maintenance would influence the risk. Conceivably, this will be done in a GIS environment, as it is user friendly and can capture an abundance of information. Moreover, since the statistical output are for pavement sections, the results are geographical data, which would make a model in GIS very suitable.

1.5 Research Outline

The introduction elaborated on the relationship between Schiphol and Heijmans and touched upon the problem that initiated this research in the first place. In the forthcoming chapters, it will be endeavored to adequately respond to the aforementioned problem. For readability purposes, the structure of this research will be firstly explained to give a clear overview of what's to come.

In Chapter 2, pertinent literature will be scrutinized to explore what is already known about this topic and to gather more insights about the consequences of deferring taxiway and runway pavement maintenance. In addition short interviews were held with Heijmans engineers, to get familiar with the internal processes and the available data. Subsequently, Chapter 3 will devote attention to the identification of the rationales for deferring maintenance through a series of interviews with pertinent stakeholders. This provides more contextual information and will be fruitful for the remainder of this research. Thereupon in Chapter 4, data about several significant factors will be acquired. These factors entail pavement age, traffic intensity, aircraft speed and pavement foundation information. Ultimately, this information will be analyzed with statistical models to reveal under what circumstances pavement failures tend to emerge and how deferred maintenance contributes herein. Subsequently in Chapter 5, the magnitude of operational impact of pavement failures will be analyzed. The gathered insights are then consolidated in Chapter 6 to erect a dynamic choropleth model that fulfills the stipulated objective. The choropleth should exhibit the pavement sections that pose the largest risk. Evidently, projects on these sections, should be prioritized when conceiving maintenance plans. Finally, this research concludes with the most pithy insights, research limitations, recommendations and a discussion.

1.6 Post Research Side Note: Covid-19

Amidst this research, the global Covid-19 pandemic emerged, which profoundly upended the aviation sector. The aviation industry was disproportionately affected by the measures and the consequences dominated the newspaper headlines several times, depicting deserted "ghost town" airports and grounded aircraft parked on runways. Fortunately, light at the end of the tunnel is appearing, as the Dutch aviation market is now gradually stabilizing and the consequences are slowly becoming clear for Schiphol. Nonetheless, the aftermath is destructive, as Schiphol anticipates a loss of €400 million for just 2020. These effects will be felt throughout the entire organization of Schiphol and by all affiliated companies. Furthermore, the effects on the MJOP plans are appearing, as the majority of the maintenance projects in the remainder of 2020 and 2021 are put on hold. Evidently, this has effect on the results of this research. First and foremost, it reinforces the need for thoroughly understanding the consequences of deferring taxiway and runway pavement maintenance, since it is occurring at unprecedented levels at the time of writing. In addition, limited financial resources was earlier identified as a reason for deferring pavement maintenance. However, this tumultuous period for Schiphol, has given "limited financial resources" a whole new dimension, as revoking projects is currently the only short-term measure to survive this downturn.

Chapter 2

Literature Review and Organizational Interviews

This chapter sheds light on the existing literature pertaining to maintenance deferment. In essence, this chapter has been separated into sections to ensure that this literature study is organized. All literature will be allocated to their corresponding section. In addition to scrutinizing literature, three interviews of approximately an hour each were held with Heijmans experts from various areas to acquire a rigorous overview of the internal practices and to reveal the available data. To structure the search for pertinent literature, the following key phrases were used in Google Scholar and Scopus.

Key Phrases: — *Airport pavement, Deferring road maintenance, Deferring airport pavement maintenance, PCI, Pavement degradation, Pavement distress, Costs of deferring maintenance*

2.1 Literature Research

2.1.1 Pavement Characteristics of Airports

Broadly speaking there are two categories of pavements, namely rigid pavements and flexible pavements. They are typically designed for a 40-year life and 15-20 year life respectively. The latter is intended to deform vertically when load is exerted and rebounds when the load is removed, it is commonly identifiable by its black asphalt or bitumen surface appearance. Rigid pavements, on the other hand, are not intended to deform [5]. Flexible pavement usually consists of the subgrade, sub-base course, base course and asphalt layer [6]. The first layer of a pavement is the subgrade, which is the naturally occurring soil. This layer must be impermeable and its volume may not vary due to frost or changes in humidity [3]. The sub-base course is the next layer and is covered by a layer of gravel or crushed stone to capture any capillary water. The base course is found immediately beneath the asphalt layer. It is usually constructed from crushed aggregates and provides load distribution and contributes to drainage. Finally, the surface of the pavement consists of asphalt, which is a mixture of coarse aggregate (45%), fine aggregate (45%), bitumen (5%), fillers (1%) and air voids (4%) [5].

Schiphol airport has six flexible asphalt runways for handling traffic, that are connected by a system of taxiways. Their primary objective is to protect the under lying ground from aircraft load and to enable a safe and effective surface for aircraft to navigate on. In essence, taxiways and runways are both constructed with sufficient strength to carry aircraft and the predominant difference between the two, in terms of composition, is that runways require a higher degree of resistance to skidding and aquaplaning. Furthermore, airport pavements are not fundamentally different from constructions used in road building, their design, construction and maintenance are identical [3, 5]. The only exception lies in the required thickness and that the runway pavement surface is covered with 5 mm of ASK (in the case of Schiphol).

2.1.2 Pavement Maintenance at Airports

Although there is no universal definition of airport pavement failure, White [5] indicated some characteristics of failed pavements: when the surface produces excessive loose stones, spalls or fragments that could be ingested by engines; when surface ponds water in wheel paths emerge; when the runway becomes slippery and affects the braking of aircraft; when the runway surface becomes unacceptably rough and makes controlling the aircraft difficult. On the other hand, Adlinge and Gupta [7] have defined a pavement failure as compromised serviceability caused by the development of cracks and ruts and Prozzi and Madanat [8] stipulated that a pavement failure emerges when the pavement condition falls below an acceptable level. This showcases that the definition of a pavement failure is primarily shaped by perception.

To prevent failures and to guarantee safe operations, the whole aerodrome pavement should comply with four basic requirements, i.e. bearing strength, good ride capability during the movement of an aircraft, good braking action and sufficient drainage capability [3]. These criteria are fundamental and complement one another. Therefore, taxiway and runway maintenance activities are performed to maintain the pavement quality at or above the desired standards. In many cases, a PCI value is determined for sections of the pavement and compared to a threshold level, this comparison indicates whether further examination is deemed necessary [9]. The primary challenge faced by airport authorities is how to justify that maintenance treatments are necessary and when [10]. This indicates that inspecting asphalt degradation and consequently determining whether intervention is necessary is subject to uncertainty, which leaves room for ambiguity in the decision making process. This issue is exacerbated by the fact that deterioration rates fluctuate, resulting in some pavement section conditions depreciating quicker below the minimum acceptable level than other sections.

2.1.3 Pavement Degradation at Airports

The degradation of asphalt is a gradual process and is the result of oxygen, light and water entering the pavement construction. This alters the properties of the binder and consequently durability issues will emerge, which makes the pavement more sensitive to climatic and traffic loading [2]. In general, the pavement will incur more damage from traffic loading than cold weather. Furthermore, Hagos [11] showed that when asphalt is poorly constructed, the binder will age significantly faster.

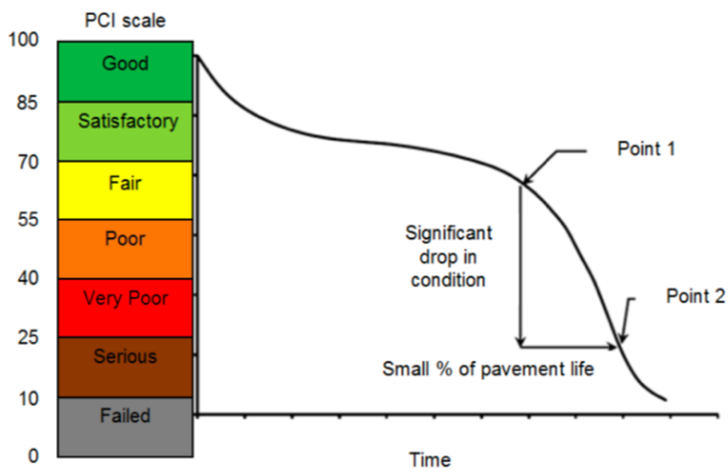


Fig. 2.1. PCI Value adopted from [12].

For characterizing the status of the pavement, the so called PCI value was established. It was introduced in the 70s by the U.S. Army Corps of Engineers Research Laboratory and aims to characterize the structural integrity and the operational condition of the pavement with a numerical score. It is not solely used for general roads, but also for airport surfaces [13]. To allocate a PCI value to a runway or taxiway pavement, one must perform a visual inspection. The amount, severity and type of distresses underpins the given PCI value. The allocated PCI value ranges from the worst condition (0) to an excellent condition (100) to the pavement. Fig. 2.1 depicts the PCI scale and the corresponding classifications.

Luo and Chou [14] provided a method to capture the type of distress, its severity and extent in formula (2.1), from thereon the PCI value can be determined with (2.2). The number of observable distresses, the distress severity and extent should be determined during a visual inspection.

$$Deduct(i) = W_d * W_s * W_e \tag{2.1}$$

$$PCI = 100 - \sum_{i}^{n} Deduct(i) \tag{2.2}$$

Where:

N= is the number of observable distresses

W_d= the weight of distress

W_s= the weight of distress severity

W_e= the weight of distress extent (size)

The types of distresses that can be identified during inspections are depicted in Fig. 2.2. These functional and structural distresses emerge on flexible airport pavements and are the result of pavement material, environmental characteristics under which the pavement is exposed, operational factors and construction process [15, 16]. They are required for determining the PCI, therefore this section will briefly describe some of the distresses, for an elaborate overview refer to Appendix A.

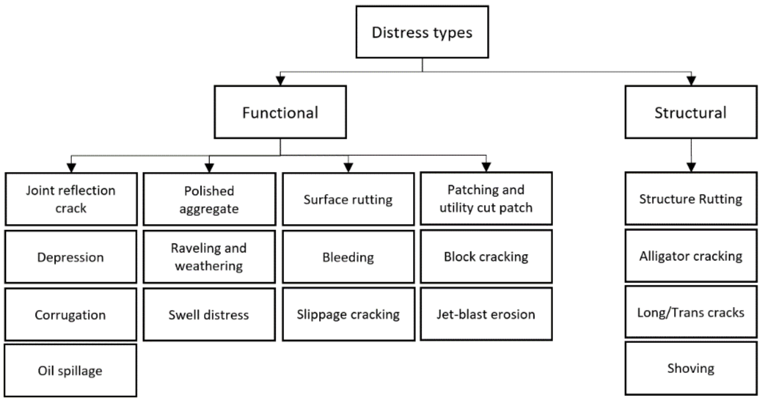


Fig. 2.2. Distress Types, adopted from [15].

One of the predominant damage types that causes degradation of the pavement is raveling. Raveling occurs when the binder loses flexibility over time and is characterized by aggregates that are eradicated from the binder due to environmental factors and traffic loading. This can produce severe Foreign Object Debris (FOD). Other distresses are the longitudinal and transverse cracking, which are not the result of traffic loading, but mainly caused by construction, material and environmental factors. In essence they lead to a functional distress.

2.1.4 Predicting Pavement Degradation

Yurchenko [17] endeavored to identify the key factors affecting the runway asphalt. With data from Air Traffic Control Schiphol (LVNL) a correlation between the pavement age, position of an asphalt piece and the asphalt degradation rate was found. The location of the asphalt piece is important because different locations receive different traffic loading, thereby affecting the rate of deterioration of structural related distresses [10]. In the study by Yurchenko [17] the runway asphalt was segregated into sections. Thereafter, each section or tile was linked to the age and the corresponding asphalt damage score, which discerns between four damage severity's (i.e. no, light, moderate and heavy damage). Notice that there are inconsistencies in the applied severity classifications (e.g. Luo and Chou [14] only differentiate between three classes). The severity of the damage was collected from asphalt inspections. Ultimately it was found that the sections that are subject to the main load from aircraft and sections older than seven years, start to show moderate and heavy cracks [17]. A peculiar observation is that less damages were seen around the Touchdown Zone (TDZ) and the central tiles than in other areas, possibly due to the fact that they were repaired immediately [17]. However, another explanation for this occurrence is the notion that the TDZ is in fact not the area incurring the highest stress. This seems counter-intuitive, but a reasonable clarification is that the aircraft still has lift during touchdown, therefore the load seldom exceeds 40% of the maximum aircraft mass [3].

A useful insight that Yurchenko [17] provided is that heavier aircraft does not imply higher damage to the asphalt, because heavier aircraft exert their pressure on the pavement through more wheels, hence distributing the weight. This occurrence is affirmed by Pasindu [10] and Kazda and Caves [3]. Furthermore, the latter study argues that, beside weight, also the type of undercarriage, number of wheels, geometric configuration of the wheel and the tire pressure play a role.

In a study by Garg and Flynn [15] a sensitivity study was conducted for flexible pavements and it was deduced that pavement life is most sensitive to aircraft gross weight, subgrade strength, and total thickness. However, in a subsequent section in this study, Garg and Flynn [15] stipulated that there is always a discrepancy between predicted pavement life and the actual pavement life, because one can never accurately reflect the operational conditions because of uncertainties in material properties, climatic conditions, changes in traffic characteristics and volumes. This implies that degradation is also a function of the amount of traffic and that predicting the pavement degradation is very cumbersome. Carvalho and Picado Santos [13] also stated that weather conditions can play a significant role in reaching unacceptable degradation levels. Despite the fact that predicting pavement degradation is highly complex, Luo and Chou [14] endeavored to find regression formulas to characterize the PCI degradation based on age. The range of R^2 in the ordinary least square regression analysis was between 0.55 to 0.66. Whereas the R^2 of the modified cluster wise regression method is from 0.85 to 0.89. However, the regressions are closer to linear than the curve shown in Fig. 2.1.

2.1.5 The Risk of Pavement Failures

The pavement of Schiphol is different from place to place, due to spatial characteristics. Therefore, the associated consequences or risks of deferring maintenance are different from case to case. To comprehend how the risk of pavement failures differs from case to case, pertinent literature was scrutinized. It appears, through existing literature, that abundant information is available regarding variables that should be considered when determining the degree of risks of pavement failures. However, as the information is scattered across various sources, the variables were firstly categorized to provide structure. To attain this, the variables were segregated into two main groups, namely "impact" and "likelihood". This notion stems from risk assessments, wherein the risk is the overarching variable determined by the level of impact and probability [18]. However, as a plethora of variables were found, it was deemed necessary to further decompose the groups into subgroups. An overview of these variables are given in Fig. 2.3.

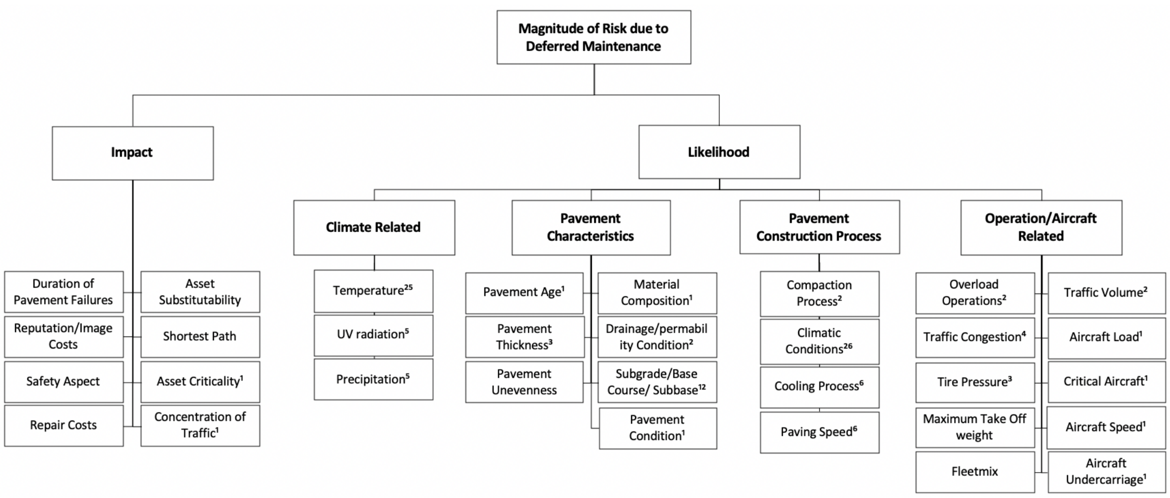


Fig. 2.3. Variables Determining the Magnitude of Risk (sources: 1=[19], 2=[20], 3=[21], 4=[22], 5=[23], 6=[24].

The depicted variables play a role in determining the level of risk. Evidently, on the one hand, there are variables that relate to the likelihood of a pavement failure occurring and on the other hand, there are variables that determine the impact. The latter is to a substantial extent dependent on the layout of the infrastructure at Schiphol. The subsequent sections will elaborate on the most important variables, by underpinning their contribution.

Impact Variables

Asset substitutability indicates whether the function of the asset can be substituted by another asset (e.g. the alternative route for taxiway Yankee is taxiway Zulu or Whiskey). With alternative routes at disposal, the operational impact remains relatively limited. Conversely, with no detour possibilities, certain areas are disconnected, which can cause an enormous disruption.

Shortest path, the extent of operational impact depends on the characteristics of the taxiway. If the shortest path is inaccessible, it means that traffic has to detour, increasing travel time and costs. The extent of traffic detour depends on the alternative route. However, this is only valid when there are alternative routes.

Traffic concentration or traffic intensity belongs to both categories. On the one hand, a taxiway which is utilized by a high traffic volume, means that it is an important node in the network. Hence, when a pavement failure occurs at that specific location, the operational impact is more severe. However, the extent of that impact also depends on the two earlier mentioned variables. On the other hand, a high traffic volume on one particular section intensifies the loading repetition, which fosters the pavement degradation [19]. These areas are more often overexploited for prolonged periods, and therefore more susceptible than assets that are less exposed to persistent loading's. The varying degree of exploitation may depend on certain factors. For instance, taxiways leading to preferred runways or taxiways with no alternatives are utilized more excessively. Hence, this causes the likelihood of failure occurrence to vary.

Likelihood Variables

Aircraft load is highly affecting the pavement. Heavier aircraft may increase the load exerted on the pavement, thereby accelerating pavement degradation, which contributes to a higher failure likelihood. However, heavier aircraft are not necessarily always more detrimental, as it also depends on the undercarriage setup and dimensions [20].

Aircraft speed is a factor that should be considered, because the extent of aircraft loading depends on this variable. Areas such as aprons, bays and the ends of runways are subject to more adverse loading conditions due to aircraft speed. As static or slow travelling aircraft are more detrimental than dynamic loads [19, 25].

Climatic conditions can foster pavement degradation. For example, due to prolonged exposure to UV radiation, asphalt will deteriorate quicker, the effect even amplifies in combination with high temperatures. Furthermore, the latter can lead to rutting disease in the asphalt pavement, in addition it allows oxidation. Finally, precipitation or water may cause a premature failure in asphalt, as it causes a loss of stiffness and structural strength, due to the loss of adhesion in the materials [23, 20]. These conditions can further aggravate the pavement condition, which increases the likelihood of a failure occurrence. However, all pavement sections of Schiphol are exposed to the same weather/climatic conditions. This renders the analysis of climatic condition, such as temperature and precipitation, impractical.

The pavement/material composition determines its robustness to environmental and loading factors [19, 20]. The composition of the asphalt layer consists primarily of bituminous, aggregates, fillers and air voids. These materials determine, among others, the extent of debonding and water penetration, and therefore the durability of the asphalt. However, underlying layers such as the base course, sub-base and sub-grade, distribute and absorb the imposed loads. Altogether, these components determine the pavement durability and the likelihood that a pavement failure appears.

The pavement condition and age determines its present rate of degradation [12]. Pavement deterioration is gradual, becoming noticeable over a period of a few years. Hence, as time progresses, the condition aggravates, which implies there is a positive correlation between the two variables. Older assets are more likely to be in a situation of compromised condition, which can pose a significant threat, that exacerbates in time.

2.1.6 Consequences of Deferring Maintenance

Tight budgets and the lack of immediate consequences make it tempting to postpone necessary repairs without thoroughly understanding the intricate and erratic implications of such delay [26]. Furthermore, decision makers try to minimize the disturbances to the airport operation, especially for important junctions that are pivotal for the taxiway routes.

Additional Repair Costs

In a report to the Congress of the United States, the US authorities were warned for consequences of deferring maintenance at small airports in the USA [27]. First and foremost, it stated that deferring maintenance will only accelerate pavement deterioration, this is the result of non-linear pavement degradation (see Fig. 2.1). Besides, the study also showed that proper maintenance will enhance the longevity of the pavement. Furthermore, if routine maintenance is not performed during the early stages of deterioration, extensive repairs will be required later, when cracks and other pavement defects progress into failures [27]. Continued deferred maintenance would shorten the runway lives on the average by about 24% [27]. On the long term, the accumulated cost of additional repair due to deferred maintenance will proliferate overtime. A study by Shahin [28] indicates that when surface treatments were implemented when the degradation level is low, savings of more than 50% on repairing costs could be achieved. For instance, according to Shahin [28], when maintenance is applied at point 2 in Fig. 2.1, it can cost four to five times more than applying several maintenance treatments while the pavement is in good condition.

Airport Operations Disturbances

The past has shown that maintenance at Schiphol can lead to a significant amount of taxiing delay [29]. The taxiing delay is denoted as the excess time needed to taxi-in or taxi-out while compared to the unimpeded taxi time, in which there is no interference during the taxiing process [30]. According to Eurocontrol [31], delays for taxiing aircraft can be quantified in monetary terms, namely at a rate of €49.5 per minute for short delays. However, these costs fluctuate based on the type of delay (e.g. taxiing, at gate or airborne), duration of the delay (significant delays result in missing connecting flights) and type of aircraft (more seats). Therefore, KLM argued that €59.5 per minute was more conceivable for this specific period, due to the summer period.

Foreign Object Debris

Consequences are not restricted to the loss of operational revenues due to disturbance to the operation or higher cost of repair or replacement. It may also lead to liability of aircraft damage due to poor or failing pavement. One of these failings is the production of loose chunks of pavement (i.e. FOD) that can be kicked up underneath a tire and cause a blow out or damage to the aircraft. Pavement that is in "good" condition has a lower chance of producing pavement related FOD and thereby damaging aircraft. Lack of maintenance, sweeping, or removal of contaminates creates a hazardous environment, which can cause damages to aircraft, and unnecessary litigation, compensation and liability expenditures. According to the Federal Aviation Administration (FAA) Advisory Circular 150/5380-5B, FOD related costs for one major airline is on average $15,000 per aircraft, which represents an industry cost of $60 million per year. Hussin et al. [32], on the other hand, estimated a direct cost of $263,000 due to FOD per 10,000 flights.

Other Costs

In a study by Chasey et al. [33] the effects of deferring maintenance were enumerated, albeit for regular asphalt roads, it can still offer some insight into the type of consequences that can be expected. The most prominent consequences were additional fuel use and higher levels of pollutants, reduced riding comfort and an increase in vehicle-repair cost. Especially additional fuel use due to taxiing delay can contribute substantially to fuel burn and emissions at airport. It is estimated that aircraft spend 10-30% of their flight time taxiing and that a short/medium range A320 expends as much as 5-10% of its fuel on the ground [34]. For instance, Simaiakis et al. [34] argued that 247 flights were incurring approximately 4.4 minutes of delay per aircraft and thereby producing 12,250-14,500 kg of additional fuel. Despite these results were published without details concerning fleet mix and taxiing and can therefore not be generalized, it does reflect the magnitude of impact.

2.1.7 Statistical Data Analysis Techniques

To measure the relationship between deferred pavement maintenance and the pavement condition or pavement failures, statistical tools can be deployed. The simplest and most frequently used statistical method to measure how quantitative variables or categorical variables are related, is the correlation analysis [35]. In the past, Yurchenko [17] analyzed the airport asphalt degradation with a correlation analysis, by fitting multiple variables. Another common statistical model that can be used to find relationships between variables is a regression model. This model is often used interchangeably with correlation analysis to denote some form of association between independent and dependent variables. This statistical model was also used by Luo and Chou [14] to analyze the relationship between the pavement degradation and the pavement age. This method can be generalized to airport pavements, as it is very similar to road pavements. The simplest form of regression is the Ordinary Least Square (OLS) linear regression, it determines an equation that minimizes the distance between the fitted line and all of the data points. In essence, the model fits the data well if the differences between the observed values and the model's predicted values are small and unbiased [36].

Other types of regression models that might be adequate for analyzing the airport pavements are Binary Logistic Regression (BLR) models, which are utilized to model the relationship between one or more predictor variables and a binary dependent variable. In BLR models, the relationship between one or more predictors and the probability of a target outcome is inherently non-linear as probabilities are constrained at 0 and 1 [37]. When insisting on using an OLS regression, the estimation of model parameters ignores this boundness. And hence, the assumptions for OLS would be violated if the dependent variable in an OLS is binary. Furthermore, a logistic regression does not apply the same residual concept, as it uses Maximum Likelihood (ML) to estimate model parameters. The latter entails an iterative process to ultimately attain a population (parameter) value that most likely produced the observed (sample) data. The final condition for applying BLS models is that the sample size is substantial, as small samples generate issues with model convergence and estimation of model parameters. Another prevalent regression model is the Poisson regression model. This model concerns data which is left-censored at zero and the data is often skewed for low sample size [38]. A fundamental assumption for applying the Poisson regression, is that the data must follow a Poisson distribution. This assumption can be conveniently tested with goodness-of-fit tests.

Alternatively to standard regression models, there are techniques that are similar to regression models, such as the Cox Proportional Hazards (PH) model, which are suitable for analyzing pavements. The latter is similar to regression models in the sense that it allows the testing of the effects of independent variables like multiple regression models [39]. This technique is derived from medical research to analyze the time elapsed to an event and can also be applied to pavements. For example, the time elapsed before a pavement failure occurred. The Cox PH model is versatile as it does not make any assumptions of the underlying survival time distribution and allows censored or incomplete data [40]. Especially for analyzing the survival times of pavements this can be helpful, as pavement data is commonly positively skewed and is subject to censoring, because the analysis time is not perpetual. Or in other words, pavements are replaced before they actually reach their termination state. In such circumstances, conventional statistical methods are not applicable (e.g. linear and logistic regression). Furthermore, the Cox PH model has the merit that, besides the time elapsed until hazard, the effects of various influential factors can be estimated through historical pavement data [40]. To summarize, the Cox PH model is a robust survival analysis technique in situations when the distribution is unknown and covariates need to be considered. Therefore, this model can be applied to understand under which circumstances pavement failures tend to emerge and evaluate the effect of the influential factors on pavement failures. This will ultimately indicate which areas are subject to a higher risk of pavement failures.

In essence, survival models are expressed as the survival function S(t). This function shows the probability of survival time being greater than time t and if T denotes the pavement service life, then the survival function can be expressed as Eq. (2.3) [40]. Or in other words, this function shows the probability that the pavement service life is greater than a given number of years. The survival probability may also be approached as an integral with t as lower boundary and infinite as upper boundary. Evidently, the probability that the service life is greater than zero is 100% (i.e. S(0)=1). On the other hand, as time passes the probability diminishes. To exemplify, the probability that the service life is greater than 10 is 0.2, which means that there is only 20% chance that the service life is greater than 10 years, ultimately $S(\infty) = 0$. Alternatively, the function may be simplified and expressed in terms of a cumulative distribution function F(t).

$$S(t) = P(T \geq t) = \int_t^{\infty} f(u)du = 1 - F(t) \tag{2.3}$$

This survival function is then used to mathematically define the hazard function, which belongs to the Cox PH model. This hazard function is based on a probability density function f(t) and the aforementioned survival function S(t). The hazard function is thus expressed as $h(t) = \frac{f(t)}{S(t)}$. This hazard function indicates how likely a pavement will fail at time t [40].

$$h(t) = h_0(t) \cdot e^{\sum_{i=1}^{n} \beta x} \tag{2.4}$$

Alternatively, the hazard function for a pavement may be written as Eq. (2.4) [41]. This hazard function for pavement failures can be decomposed into two respective parts. The former is the baseline hazard function and the latter is the exponential expression e to the linear sum of βx [41]. As the formula concerns $e^{\beta x}$, a $\beta < 0$ is associated with lower risks and longer survival times, whereas a $\beta >$ 0 implies the opposite. For example, if the hypothesis: "pavements subject to higher static loads have a lower survival time" holds true, the corresponding β will be a positive coefficient. Hence higher static loads has negative effects on the service life. This β is approximated by maximizing the partial likelihood [40]. Rewriting this equation yields Eq. (2.5). Similarly, the model can be regarded as a log-linear model.

$$h(t) = h_0(t) \cdot e^{\beta_1 x_1 + \ldots + \beta_n x_n} \rightarrow log[h(t)] = log[h_0(t)] + \beta_1 x_1 + \ldots + \beta_n x_n \tag{2.5}$$

2.2 Organizational Interviews

To get acquainted with the internal processes of Heijmans and to identify the available data to work with, short interviews were held with Heijmans engineers. These interviews were effective and helped to narrow down this research, as it revealed the information and data that is at disposal. The subsequent sections will address the findings from these short interviews.

2.2.1 MJOP

Maintenance plans that will be performed in the future are outlined in the Onderhoud Jaar Plan (OJP) and MJOP. The latter concerns large maintenance activities with a maintenance interval exceeding three years and is for the forthcoming five years. Conversely, the former shows the smaller maintenance on the short term. The predominant objective of the MJOP is to conceive a plan that is feasible in terms of constructability, attainability and financeability. Furthermore, it must adhere to the asset performance indicators, while transparently considering the associated performances, risks and the costs. In essence, the MJOP maintenance plans for the upcoming five years are determined by annual pavement inspections, FMECA's and annual (recurring) maintenance activities. This MJOP indicates where maintenance will be conducted, the corresponding costs and when the maintenance is initially planned and when it will be actually conducted.

During annual pavement inspections an inspection vehicle makes pictures of the pavement. These pictures will be examined to perceive the current state of the taxiway and runway pavement.

Through these inspections it became evident that only a few types of distresses emerge on the pavement of Schiphol. Fig. 2.4 showcases which distresses are predominant and their corresponding severity for the airport pavement.

[redacted]

Fig. 2.4. Distress Types Observed at Schiphol Airport.

As mentioned before, the observed distresses during annual pavement inspections determine the PCI value. The starting point of this process is to determine the type of distress. Thereafter, the corresponding deduct graphs must be found. Thereafter, the evaluator must determine the distress severity and density. The severity can be classified in three classes and the density is simply expressed in percentages indicating the area of distress. After the deduct values have been determined, the final PCI value can be determined through a set mathematical equations.

For Schiphol the PCI values are depicted in Fig. 2.5. These PCI values were handed over in 2018 by Schiphol to Heijmans, however this does not imply that the PCI measurements originate from 2018. In some sections the PCI values, as indicated in Fig. 2.5, were measured over a decade ago. This justifies why some sections are well below a PCI of 55. Unfortunately the PCI data before 2018 is very scarce, only PCI data from 2018 and 2019 are well recorded.

[redacted]

Fig. 2.5. PCI Values for Schiphol 2018.

2.2.2 Pavement Age and Failures

Heijmans has recorded the age of the pavement layers at Schiphol. Fig. 2.6a highlights the pavements that have been installed in 2003. Furthermore, when pavement failures manifest on the pavement and are observed by Schiphol, Heijmans will be contacted to prepare and perform the repair maintenance. Heijmans has recorded all the incoming pavement failures from April 2019 and onwards. In Fig. 2.6b the failures between April 2019 and February 2020 are depicted on the Schiphol map. Attributes to these data points are their priority and the type of failure. In the map it is noticeable that the failures are not randomly scattered and that the majority are at the bay areas. This type of data can be essential in finding correlations between deferring maintenance and the amount of failures that are occurring. However, the majority of this data (before 2019) is merely qualitatively recorded. To include them in the Fig. 2.6b and to draw any conclusions, the qualitative data must be converted to Global Positioning System coordinates (GPS).

[redacted]

(a) Pavement Age **(b)** Pavement Failures in 2019

Fig. 2.6. Pavement Age and Failures at Schiphol

2.2.3 Maintenance Wear Out strategy

Throughout the life cycle of a taxiway and runway pavement, the pavement condition gradually deteriorates. Simultaneously, the rate at which the condition declines, accelerates and ultimately maintenance is necessary [12]. This will recover the functional and structural integrity of the pavement to its initial condition or a fraction of it. Fig. 2.7 depicts the theoretical condition development over the pavement life cycle. In this overview, large maintenance is conducted when the condition intercepts the intervention level, this inhibits the condition to attain the failure level [42]. A more implausible scenario, but theoretically possible, is to omit this maintenance moment and to let the pavement condition aggravate until it has fully worn out. However, this goes hand in hand with higher risks, more failures for both the pavement and the operators.

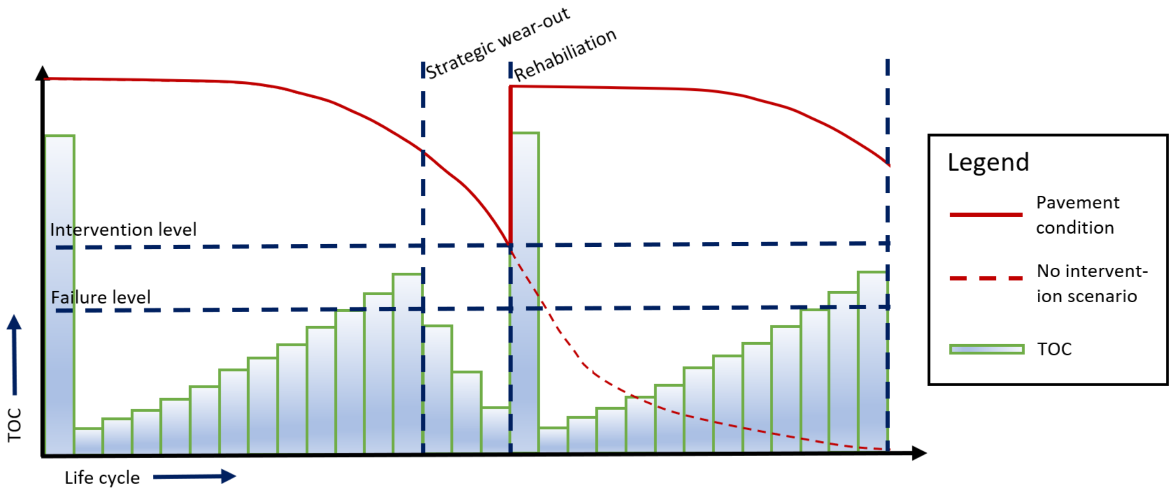


Fig. 2.7. Pavement Life Cycle Maintenance Strategy.

At annual basis, inspections and small maintenance are conducted. In Fig. 2.7, it is shown as the Total Cost of Ownership (TOC). The capex are high during large maintenance, however, it will substantially reduce the costs of small maintenance. Over time these costs will proliferate, until it is financially injudicious to continue without large maintenance. Hence the decision to conduct large maintenance is not solely based on the pavement condition, but also on the economic feasibility. However, in the current strategy, applied by Heijmans and Schiphol, the emphasis lies heavily on predictability as their decisions affect many stakeholders. Therefore, a large maintenance planning was conceived, which outlines that large maintenance is conducted on the runways at an interval of approximately 15 years and 7 years for TDZs. In addition, the deployed resources in the years prior to large maintenance is lower, which follows the principle of a so-called "wear-out strategy".

2.2.4 Surface Deflection Measurements

Beside the asphalt deterioration, Heijmans also measures the condition of the pavement foundation. This is done by measuring the surface deflection, which is an indicator for the pavement foundation condition. It characterizes the load-carrying capacity of the entire pavement [43]. Moreover, in the past it was even used as an indicator of the airport pavement life. The instrument to gauge the surface deflection is called the falling weight deflectometer. The instrument imparts a rapid and nondestructive transient load on the pavement surface. This exerted load, mimics the duration and magnitude of a normal load pulse induced by an aircraft moving at moderate speeds [43]. Ahlvin [44] showed that when an aircraft wheel load would cause a deflection of about 0.25 inch, a failure is expected in the near future under repeated loading. Therefore it is hypothesized that pavement failures can be caused by a high deflection. In addition, it is well known that asphalt tends to harden with the passage of time and that the properties are undergoing constant change because of oxidation, loss of volatiles and increasing density under the action of traffic [45]. Therefore, this deflection will vary from location to location and hence, it could increase the risk for certain areas.

In Fig. 2.8, the measurement setup is depicted. It shows the falling weight deflectometer on the left, which releases a weight from a given height. The height can be freely chosen, which allows the simulation of varying magnitude of loading's that are exerted on the pavement surface (e.g. 20 kN up to 250 kN). However, the imparted load could vary from location to location, therefore the measurements will be normalized through linear extrapolation [46].

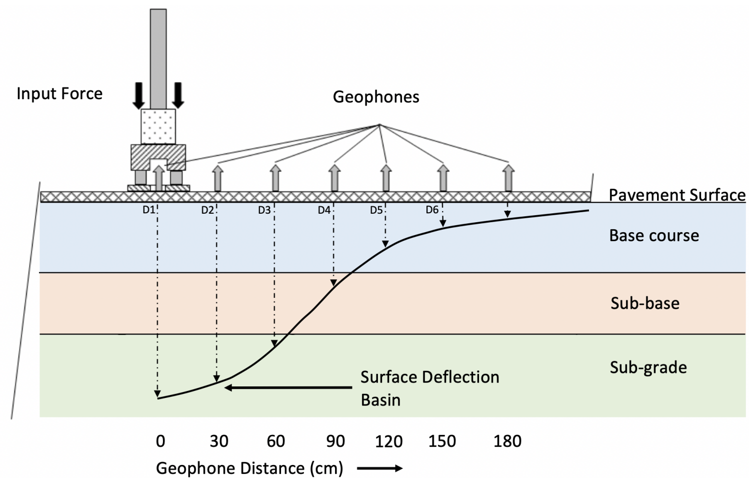


Fig. 2.8. Schematic Overview of a Falling Weight Deflectometer.

The geophones, shown on the right side of the deflectometer, measure the extent of deflection (which is expressed in μm). In general, seven or more geophone devices are placed at certain distances from the point where the load is transferred. After these measurements, the load-carrying capacity of the pavement is determined [46]. It must be mentioned that this load-carrying capacity decreases due to loading repetition, this effect is known as fatigue. Furthermore, because asphalt is a substance, the results are susceptible to heterogeneous conditions, therefore it is important that the temperature of the material and the load duration are similar for each measurement [46].

As the pavement foundation has a relatively high longevity, the load-carrying capacity is only measured at an interval of ten years. The sampling procedure for measurements is determined by the analyst. However, conventionally, the measurements are conducted at a certain distance interval, alternating between the left, right and on the aircraft wheel paths. A practical example is shown in Fig. 2.9, which shows the precise locations of where the samples were taken. The numerical values attached to every measurements shows the horizontal distance between the given sample and the start point. Hence, for this particular deflection test, the measurements commence on the centerline and gradually move to the left of the centerline (as seen from the measurement direction). This process is repeated every ten meters. In total, the measured area at Alpha 12, was around 300 meters long.

After the measurements are concluded, the results are processed in a deflection graph. An example of a deflection graph is depicted in Fig. 2.10. It shows the extent of deflection on the vertical

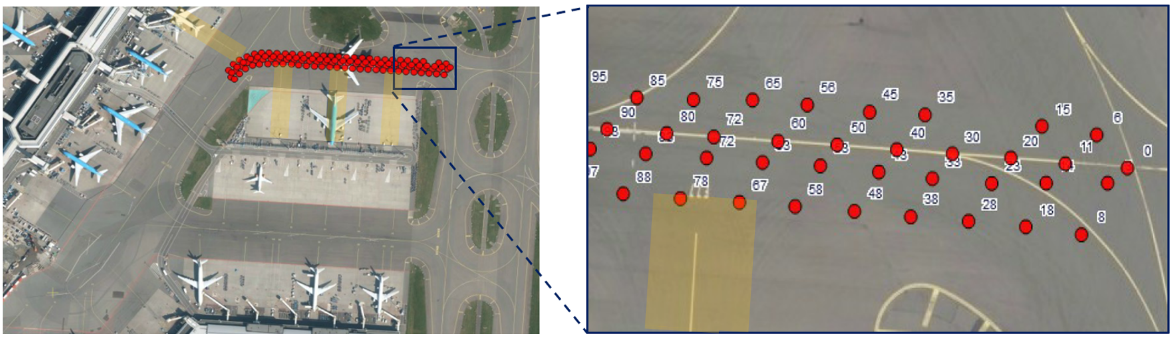


Fig. 2.9. Pavement Surface Deflection Measurements at Alpha 12.

axis, whereas the horizontal axis shows the corresponding measurement in distance from the starting point. For instance, the last measurement in Fig. 2.9 is shown as "296", this coincides with the last measurement shown in Fig. 2.10. The deflection graph shows three different results, namely the 0 Geo, 2500 Geo and IDK 600. The former shows the measured surface deflection at the first geophone, whereas the 2500 Geo shows the surface deflection at 2500 mm from the first geophone. Finally, IDK 600 shows the difference in surface deflection between the first geophone and the geophone at 600 mm. This is valuable information, as it shows how the load is distributed to the adjacent pavement. Hence, when the surface deflection basin in Fig. 2.8 is very steep with a narrow distribution, the pavement condition is considered poor. At contrary, if the deflection shows a very distributed result, the pavement condition can be considered healthy [45].

[redacted]

Fig. 2.10. Deflection Measurements Graph of Alpha 12.

To illustrate a factor that might cause an increase in surface deflection, four rectangles have been depicted in Fig. 2.10. These are the measurements in the wheel path during push-back of an aircraft. They are at, respectively, a distance of 0.07-0.09/0.14-0.16/0.21-0.23 and 0.27-0.29 km. When examining these measurements in the deflection graph, it can be observed that the corresponding measurements in the push-back zones are consistent with the highest peaks. As most of the other circumstances are similar for the pavement at Alpha 12, this could be a signal that the push-back maneuver can alter the carrying capacity of the pavement. Nonetheless, conclusions cannot be prematurely drawn, as other effects might be present (e.g. curvature sections). The effects of other factors can be further investigated, as ample information is available. However, because the primary emphasis of this research does not concern the pavement deflections, no further attention is devoted to the factors that cause a varying surface deflection.

2.3 Chapter Conclusion

The literature review has provided a better overview of the existing literature on deferred maintenance and the possible consequences. Due to a lack of literature about this topic for airports, the literature review was extended to road maintenance. Overall it can be deduced that the consequences of deferring maintenance for taxiway and runway pavements is seldom explored, let alone quantified. This stresses the presence of the knowledge gap and reinforces the need for research.

Although literature pertaining to this particular topic is scarce, still some important insights were found. Firstly, data pertaining to pavement failures on Schiphol was found. These failures could have led to traffic detour and since the cost of taxiing delays were found, the costs of these pavement failures for airlines can be quantified. If there is a correlation between pavement failures and maintenance deferment, these operational costs can also be directly linked to the latter. However, this implies that it is necessary to first investigate whether pavement failures are the consequence of deferring pavement maintenance.

Secondly, in Section 2.1.6 it was indicated that deferred maintenance may lead to additional repair costs and can have implications on the long term. Hence, deferring pavement maintenance may indeed entail adverse consequences. However, these findings cannot be generalized, because it is related to small airports, which is exposed to less airport operations and smaller aircraft types. Furthermore, exact consequences were only qualitatively indicated and therefore imprecise. This implicates that still much is unknown about this topic, hence further research is required.

Fig. 2.6 depicted that information about the pavement age and pavement failures are readily available. This information can be analyzed with the statistical models that were identified in Section 2.1.7, to comprehend whether the pavement age contributes in the development of pavement failures. In addition, other parameters or influential factors from Section 2.1.5 can be incorporated into the statistical analysis to analyze whether they play a role in the emergence of pavement failures. This can directly contribute to the research objective of this research.

Chapter 3

Rationales for Deferring Taxiway and Runway Pavement Maintenance

In the foregoing chapters, it was mentioned that limited financial resources may be one of the reasons for deferring taxiway and runway pavement maintenance. Furthermore, it was hypothesized that deferment of pavement maintenance is inevitable. To identify the validity of this notion and to comprehend whether there are other underlying reasons for deferring pavement maintenance, a research question has been dedicated to this topic. To find the answer to this question, interviews will be conducted, as outlined in the research design. However, since this is a complex topic, it would do no justice to merely answer this question without understanding the full context. Therefore, attention will be firstly devoted to understanding to what extent pavement maintenance is deferred and at what intervals. Thereafter, the interview will be conducted to reveal information pertaining to the entities within the organization of Schiphol that are responsible for deferment and the underlying rationales.

3.1 Extent of Maintenance Deferment

Before advancing towards the interviews, the extent of deferring pavement maintenance will be analyzed. Familiarization with these details is pivotal for conducting the interviews, because certain projects can serve as examples during the interviews. In essence, the MJOP and other pertinent documents are used to analyze the extent to which the pavement maintenance is deferred. This MJOP document stipulates the planned (large) maintenance on taxiway and runway pavements for the five forthcoming years. The concept MJOP is conceived by Heijmans and then reviewed by Schiphol. The latter has the authority to request alterations to the initial MJOP, consequently, Heijmans has to process the requested amendments. Eventually, the definitive MJOP will be presented. To get acquainted with a MJOP, refer to Fig. 3.1 for the Schiphol Parcel one MJOP 2019-2023.

[redacted]

Fig. 3.1. MJOP 2019-2023.

The MJOP highlights the scope of maintenance works per year and each activity in this overview is denoted with a corresponding name. Furthermore, there are supplementing documents for every separate maintenance activity, that underpins why each activity has to be conducted and what type of works it entails. For instance, the maintenance works on taxiway Zulu, entitled "P1 GOH 176, was initially planned for 2019 back in 2015, but deferred to 2020 by Schiphol. The working scope includes pavement milling of the existing asphalt layer and to, ultimately, create a new asphalt layer on taxiway Zulu. Hence, these documents also indicate when the initial maintenance activity was planned and when the maintenance actually materialized. To capture the extent of maintenance deferment and where it actually occurred, the current MJOP and its predecessors were analyzed. Merely the deferred maintenance activities that were initially planned between 2015 and 2022 were assessed. Other maintenance activities that were either performed on planning or before the planning were omitted. Eventually, a list of 19 deferred maintenance activities was found. These activities were then linked to their corresponding location on a map, using GIS as depicted in Fig. 3.2.

[redacted]

Fig. 3.2. Deferred Maintenance Activities in the MJOP between 2015-2022.

In essence, it can be inferred that the majority of the maintenance activities are deferred by two years. In some extreme occasions, such as the Romeo platforms (GOH 157), the maintenance was even deferred for at least four years. Furthermore, the maintenance on taxiway Alpha 8 (GOH104) was deferred by three years, from 2016 to 2019. When using information pertaining to the asphalt age, which will be further discussed in Chapter 4, the time between paving and eradication can be determined (i.e. pavement age at removal). When doing so, it becomes evident that some pavement sections will be older than 18 years when replaced, due to deferred maintenance (see Table 3.1). The table shows in which year maintenance will be conducted on the pavement, according to the latest MJOP (accounts for postponed maintenance). Besides, it also shows in which year the pavement layer was paved. By comparing both numbers, the age of the pavement at replacement, can be computed. In essence, each of the pavement sections are three or more years overdue according to organizational documents, when a replacement interval of 15 years is considered.

Table 3.1. Pavement Section Age at Replacement.

[redacted]

3.2 MJOP Conception and Involved Parties

In the series of interviews, four insiders from Schiphol and Heijmans were interviewed. More information about the interviewees, the interview strategies and the questions are described in Appendix B. In addition, it depicts the interview transcripts and elaborates on how the qualitative interview data is processed and subsequently tabulated to easily extract information from the bulk of details. This chapter will proceed with presenting the interview results.

Through the examination of organizational documents and interviews, it was found how the MJOP is conceived (see Fig. 3.3). In principal, it commences with the ASM Asset Continuity department that provides the demarcations of the MJOP to Heijmans. Adherence to these boundaries is essential to conceive a MJOP that is feasible in terms of attainability, constructability and financeability. The process of obtaining this information commences in March (2019) and is orchestrated by the Reliability Engineer.

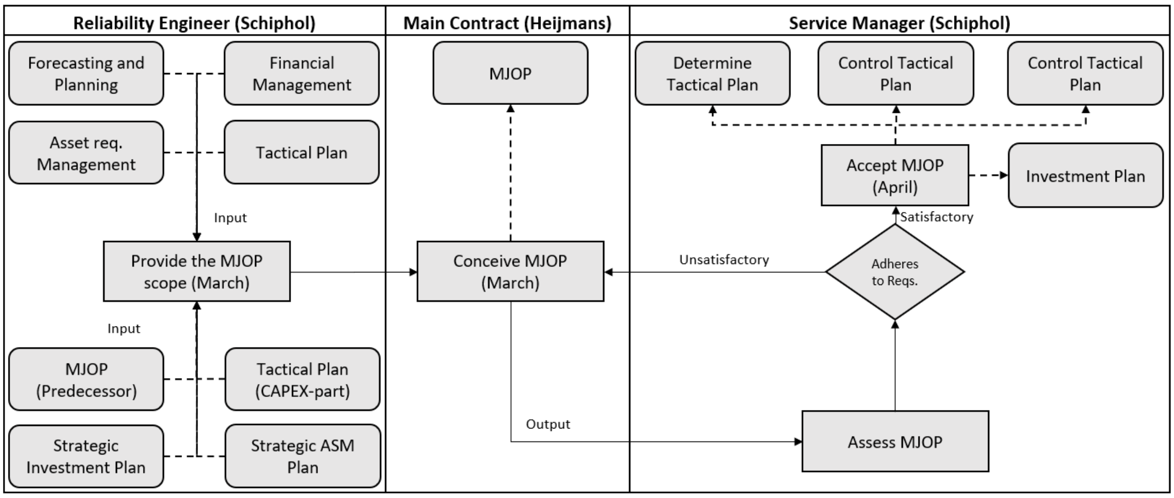


Fig. 3.3. MJOP Formulation Flow Chart.

In the following phase, these details are then consulted with Heijmans and reciprocal interaction will ensure that a foreseeable MJOP is submitted to the ASM department in March (2020). It is worth mentioning that there is a pronounced shift in responsibility between these phases, namely from Schiphol to Heijmans and back to the former. Upon receiving the MJOP by Schiphol, the service manager is compelled to assess whether the MJOP adheres to the predefined boundaries within 21 days. This implicates that the MJOP must be accepted before April. Thereafter, Asset Continuity passes the MJOP over to the ASM Development department, this also marks the transition from the plan development phase to the planning phase. In this phase, the Systems Developers from the Development department enter the process (shown on the right top of Fig. 3.3). From thereon the Project Managers are involved and ultimately the loop is concluded with the implementation phase, which is primarily Heijmans' remit. This was briefly an overview of the process of gathering input information until presenting the definitive MJOP. Evidently, in every phase of this process there are different parties involved.

Schiphol is a large complex organization with many layers and internal parties (e.g. finance-, operations- and engineering services department). Consequently, there is a strict internal division in responsibilities, which implies that every entity within the organization governs their own discipline and has their own interests. The process of conceiving and revising the MJOP requires the attention and permission of a multitude of parties. To comprehend which parties have a considerable contribution in the MJOP conception and may impose modifications to the initial plan, a stakeholder analysis was conducted to reveal the involved parties and their respective position herein. The definition of a stakeholder in this analysis is derived from Ramirez [47] and is as follows: *"Any group or individual who can affect, or is affected by, the achievement of a corporation's purpose."* In this particular case it concerns departments that can affect, or is affected by, the process of MJOP conception and its modifications. Pertaining to the stakeholder analysis itself, the framework provided by Graaf et al. [48] was used. This framework commences with the identification of the involved stakeholders, for this purpose, information was derived from organizational documents and the interviews. The identified stakeholders are enumerated in Table 3.2.

Table 3.2. Stakeholders of MJOP Conception and Modification.

Stakeholder Name	Stakeholders Responsibility
Airlines (e.g. KLM)	The airlines are involved in the consultation meeting which is organized between Schiphol and airlines. In this meeting Schiphol is presenting the tactical plans, which also encompass MJOP projects. Since the majority of Schiphol's revenue streams come from the airlines, they may exert influence on the plans (60% of the net revenues in 2019 came from airlines) [49]. However, this relates predominantly to new development plans, which may indirectly impinge on the MJOP plans.
Airport Operations (OPS) and Works & Asset Planning (WAP)	OPS orchestrates and facilitates all pertinent activities related to airport operations. Among others, they ensure availability of the airport for landing or departing aircraft. And since the core business of Schiphol revolves around the airport operation, it is of utmost importance to consult with this department to reveal the operational constraints for maintenance activities. WAP on the other hand, is responsible for work-coordination and seeks the balance between construction related activities and the airport capacity.
Asset Management department	ASM is primarily responsible for asset management of the operational assets of Schiphol. This may entail realization of new assets and modifying, managing and maintaining existing assets. ASM is the overarching department and also encompasses the Asset Continuity- and Development departments.
Asset Management Asset Continuity	Asset Continuity is responsible for Schiphol's agreement compliance with asset users (airlines) about assets and service performance standards. This department is decomposed into various domains, for this research the most relevant one is the outside cluster. This entity is primarily responsible for the MJOP. As one respondent explained it: "They coordinate the MJOP process for airside, they also make the considerations together with operations and the MJOP projectboard. Ultimately, the decision is made there." In the end, the plans to initiate a new construction project, is handed over by Asset Continuity-Outside Cluster to Development-Realization-Outside Cluster.
Asset Management Development	Development is composed of the Plan Development, Airport Development and Realization domains. Each domain is then further decomposed into an in- and outside cluster. The remit of the latter is the initiation of new development or maintenance projects on airside. Moreover, it is the internal client for a new project and is designated to give the assignment to the project management entity (i.e. PLuS).
External Parties	External parties are indirectly affiliated with the MJOP plans, because they can influence Schiphol's policies. The external parties include the Ministry and Municipality of Amsterdam, as they have a considerable share in Schiphol, respectively 69.77% and 20.03% [50]. Furthermore, as Schiphol has a socio-economic function, the priorities and opinions of the residents in the vicinity are also important. Albeit their degree of power, to exert influence on the MJOP plans, is inferior to other parties, they still have a certain interest.
Luchtverkeersleiding Nederland (LVNL)	LVNL provides the air traffic control services and is heavily involved in the airport operations [51]. Furthermore, LVNL has assets on Schiphol hence, for some projects Schiphol has to ask permission from the LVNL.
MJOP Project Board	The projectboard resides at the highest management level for a given project. It represents the interests of the customers, users and suppliers and determines the direction of the given project. It is formed by delegates from various departments.
PLuS and CAP	PLuS and CAP are the providers of management, support and financial monitoring of projects. It is a versatile department, as they are involved in disciplines such as construction, mechanical-, electrical- and civil engineering. Ultimately they receive the construction assignments from Development.
Portfolio Management	Portfolio Management is responsible for the finances and is the orchestrator of the consultation. Furthermore, the tactical plan is administered by this department.

After the identification of the stakeholders, it was necessary to provide insight into the stakeholders' position because it reveals how important stakeholders are with their respective demands. For example, stakeholders that have high power and high interest are more likely to influence the current MJOP plans. Conversely, stakeholders with a high power and a relatively low interest, possess the power to demand for alterations, but is only done sporadically (e.g. municipality or ministry). For this purpose, the identified stakeholders were depicted in a Power-Interest matrix to indicate their respective position in the power- and interest continuum of MJOP conception and the modifications to it (refer to Fig. 3.4). Moreover, it was explained that the process of MJOP conception must strictly follow the attainability, constructability and financeability restrictions. Therefore, to discern the different stakeholders at ease, the Power-Interest matrix also exhibits the domain that is administered by the given stakeholder. These domains were deduced based on the insights from the interviews.

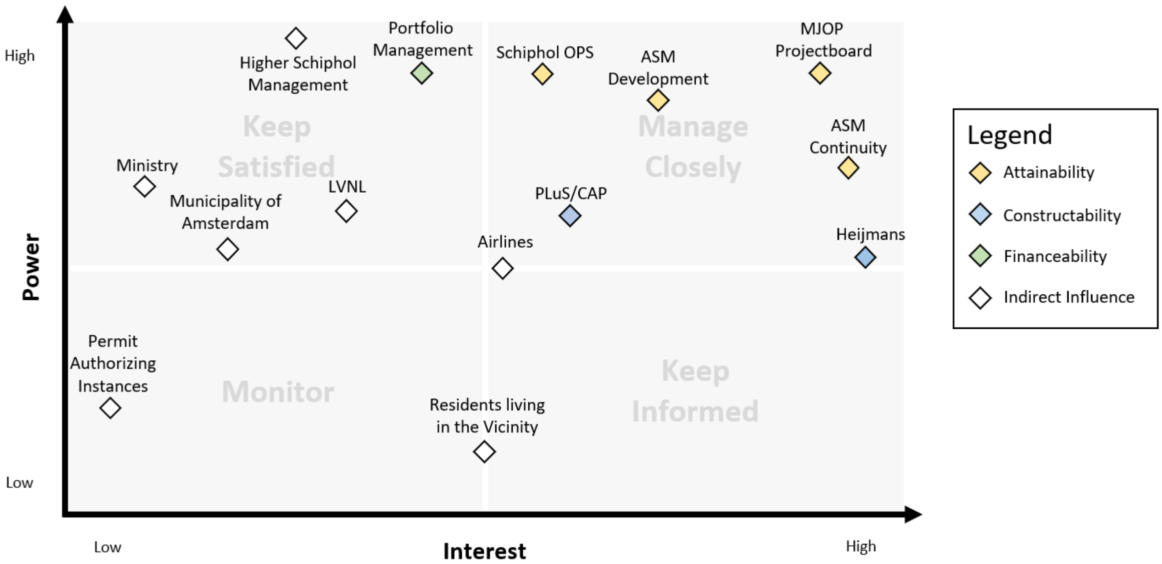


Fig. 3.4. Power-Interest Matrix of Stakeholders.

3.3 Rationales for Deferring Pavement Maintenance

To provide transparent results, a qualitative overview was erected in a system dynamics environment. The overview discerns between three layers like an onion model. Each layer indicates the extent to which the particular factor can be decisive in deferring maintenance. This was determined based on the narratives of the interviewees, in which it was repeatedly asked to rank the factors. The complete overview is shown in Fig. 3.5, take notice that the preceding subsection clarified the affiliation between certain departments or processes, which is necessary for the readability of this section.

3.3.1 Primary Causes

In principal, from the thematic data analysis it was inferred that limited budgets and operational restrictions form the largest reason to defer taxiway and runway maintenance. The former can be attributed to various stakeholders, whereas the latter is mainly imposed by Schiphol OPS and WAP. However, it must be stressed that the pre-definitive MJOP plans are conceived in accordance with the attainability, constructability and financeability triangle. Nonetheless, these plans are still subject to change, even after acceptance.

Regarding the budgets, Schiphol charges airport levy fees on airlines, which makes this the primary revenue stream source as explained in Table 3.2. In prosperous times, when the aviation sector is flourishing, there is more flexibility in terms of finances. However, as soon as the economy contracts, the available financial resources become tighter. Although sporadic, these circumstances have

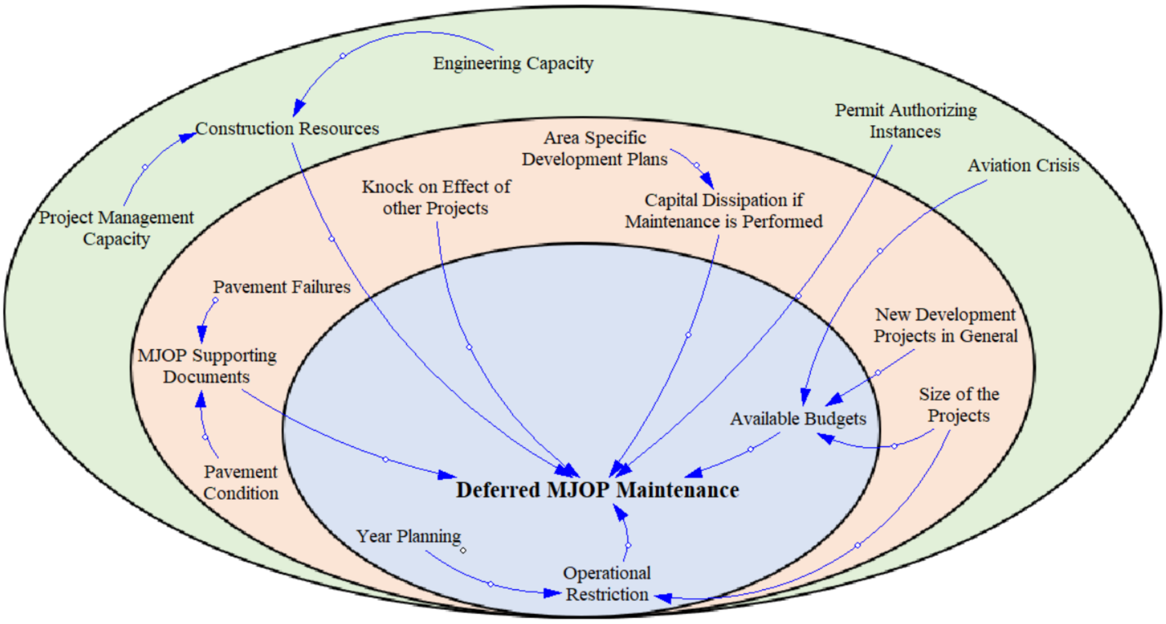


Fig. 3.5. A Qualitative Model Exhibiting the Reasons for Deferring Taxiway and Runway Maintenance.

significant impact and as a consequence maintenance can be deferred due to limited budgets. Therefore it is essential that maintenance activities are prioritized and the associated risks with postponing certain maintenance activities are evaluated. As one of the respondents mentioned.

> “You can imagine that when we are discussing the budgets for 2022 to 2025 in the consultation meetings, with the knowledge that airlines are currently receiving state aid, they are not waiting for high airport fees. Hence, they will probably exert substantial pressure and ultimately we will receive limited income flows. I reckon it is going to materialize.”

Furthermore, one of the respondents acknowledged that within asset management there is an internal conflict about prioritization of resources (e.g. Development and Continuity). Schiphol has also addressed this as a construction project threat in their annual 2019 report and expressed their concerns about the lack of integration between different project delivery departments, leading to clashes, delays and arguments over prioritization and resources. According to the respondent, project managers have an intrinsic tendency to prefer new development projects and hence there is more attention and resources available for these projects. It appears that maintenance is less exciting and therefore a victim to sacrifice. In addition, airlines have the power to articulate their wishes during the consultation meeting. Their preferences also tend to advocate investments in new projects, since their benefits are more explicit. As one of the respondents explains:

> “You know the merits of new development projects. A new platform? Well, we can park three airplanes there. Okay we want that, because it will directly contribute to our revenues. For maintenance the benefits are less explicit.”

Hence, it can be said that the prioritization of new projects over runway and taxiway maintenance is twofold, namely from certain departments within Schiphol and airlines. It is not that people are reluctant to spend money on maintenance, but when the budgets are tight and trade-offs have to be made, there is an inclination to sacrifice maintenance. However, it must be mentioned that one of the respondents refutes this notion, as he firmly believes that budget allocated to maintenance is solely for this purpose.

Finally, it was mentioned that when a maintenance activity has a scope which is too large, it may happen that OPS or WAP demands a separation of the initial project into smaller segments and that some of them are deferred. The rationale behind this decision is that it would otherwise not comply with the operational and financial restrictions. The scope of a project can always be enlarged by overruling departments. For example, when the implementation phase is nearing, the particular maintenance activities show up on the radar of internal stakeholders that were not precisely aware of what was to come. Hence, it may occur that some of them request for additional projects that are merged with the original plans, because they have interfaces. On the one hand, synergistic advantages can be found and more work can be done within the same time frame, given that the additional projects fit in the critical path of the initial maintenance project. On the other hand, the additional projects will increase the spatial scale of the initial project. Furthermore, budgets were requested and obtained prior to these events and since financial resources are not that flexible, still certain parts of the activities must be deferred. So in essence, tight budgets and a combination of underlying mechanisms have a major contribution in deferring taxiway and runway maintenance.

Regarding the operation, which is governed by OPS, Schiphol is a 24/7 business and the airport operation is of utmost importance. At certain moments it is simply not permitted to conduct maintenance on important taxiways and runways, for example during the May and summer holidays. During the interviews it was repeatedly emphasized that the operation forms a prominent bottleneck. As one of the respondents puts it:

> “
> When conceiving the MJOP plans it is essential that you seek explicit cooperation with OPS to evaluate the attainability of the plans. They are the largest bottleneck. When you remove this peril, you have accomplished good work.
> ”

To exemplify the importance of the operation, OPS and WAP have the policy that only a limited amount of aprons may be unavailable or inaccessible. This is due to the fact that airplanes are continuously arriving and departing and that apron facilities are scarce. By obstructing the aprons, less airplanes can be accommodated or some airplanes have to be averted to other aprons that are at an unfavorable distance from the terminal. This shows how taxiway maintenance in the vicinity of aprons can often be hampered by the operation. Conversely, taxiways that are perceived as less critical for the airport operation, require less negotiations to defer. As one of the respondents puts it:

> “
> There are various taxiways that can navigate you to the Polderbaan, like taxiway Yankee. Yet, there are seldom negotiations regarding the MJOP plans of taxiway Yankee. I presume that Schiphol reckons that this taxiway is less critical, because there are other taxiways that can easily accommodate this function.
> ”

This exemplifies that indeed, certain assets require less negotiations, despite that the expenses of replacing taxiway Yankee is approximately €4 million. This shows that the extent of operational impact of a maintenance project, is a significant factor to take into consideration when prioritizing the pavement maintenance projects.

3.3.2 Secondary Causes

A secondary cause for deferring maintenance that was repeatedly mentioned, is a knock-on effect from other projects. Broadly speaking, MJOP projects are spatially independent. However, since they share common financial resources, they are to some extent connected and therefore in some occasions maintenance was deferred, like at the Polderbaan (2018-2021) and the Aalsmeerbaan (2021 to 2022). The former was deferred because of a knock-on effect provoked by the Kaagbaan, according to one respondent. The source of the problem was the scope definition of the Kaagbaan, discussions were still going on shortly before the start of the Kaagbaan rehabilitation. So in essence, for this specific case, the engineering and preliminary investigation was unintentionally consuming more time than initially planned. Therefore, Schiphol was not prepared for another large project which would quickly follow, namely the Polderbaan rehabilitation. Consequently, large maintenance on the Polderbaan in 2018 was replaced by smaller maintenance, to extend the lifespan of the Polderbaan by three years and then ultimately in 2021, the large maintenance will still take place. Then pertaining to large maintenance on the Aalsmeerbaan in 2021, according to the latest version of the MJOP, this will now be performed in 2022 (Section 3.1. Again, the source of this deferment is a knock-on effect of another project. However, in this particular case there was a different culprit, as it was caused by the fact that Schiphol does not perform large maintenance on two runways concurrently nor consecutively within one year, according to one of the interviewees.

Furthermore, multiple respondents have identified that area specific development plans are also a cause for deferring maintenance. However, one of the respondents acknowledged that this is primarily the case for terminals and that this seldom occurs for airside, with the exception of the Romeo platform and taxiway (2019-2023). In this specific case, there are abstract plans for realizing new developments and therefore it would be capital dissipation to conduct maintenance there. On the other hand, the lifespan of taxiway Romeo is nearing its end and issues start to accumulate more rapidly, hence there is a decision problem. For now, the notion that a new development will take place in the near future, outweighs the costs associated with the issues at taxiway Romeo. As one respondent puts it:

> "Nobody wants to be responsible for making the call to initiate the project, because we have development plans for this area. It is no exception that it could take 10 years before initiation, this is the main culprit."

3.3.3 Tertiary Causes

As a tertiary cause, permits were mentioned. A recent example are the PFAS regulations. However, it is not limited to this particular matter. It is also possible that external parties such as the LVNL and ProRail have to consent and provide permits, because their assets have interfaces with Schiphol's assets. Furthermore, limited budgets was identified as a primary cause earlier on, however it may stem from different sources such as an aviation crisis. Considering the likelihood of one occurring, it was decided to characterize this cause as a tertiary cause.

3.3.4 Results Discussion

The preceding sections elaborated on the causes of taxiway and runway maintenance deferment. However, the interviews also provided additional information, which is equally important. First and foremost, Schiphol has formulated a runway strategy plan. This plan outlines when heavy maintenance is planned for which runway for the upcoming 50 years. The introduction of this plan provides more stability and predictability, moreover it makes the maintenance plans for runways less susceptible to change. External municipalities and other stakeholders in the vicinity of Schiphol are also expecting that Schiphol is strictly adhering to this plan. As Schiphol wants to retain a healthy relationship with its stakeholders, there is more assurance for alignment with the current runway strategy plans and less incentives to deviate. But then again, there is always a slim chance that higher management of Schiphol or the Ministry of Infrastructure and Water Management demands a modification or a new project, that misaligns with the current plans.

Secondly, during one of the interviews it was mentioned that a pronounced shift is taking place, as important stakeholders start to realize how an asset malfunction may provoke significant disturbances. This re-emphasizes the criticality of taxiway and runway assets and that their functional and structural integrity should be maintained at sufficient levels. This puts maintenance on existing assets, higher on the agendas of policymakers.

Thirdly, the preparation phase of the MJOP was mentioned various times. By commencing well in advance, one can eliminate or overcome the already identified perils. For instance by intensifying the bonds with important stakeholders such as OPS. Finally, substantiating documents that explicitly underpin the urgency of a maintenance activity, helps in the prioritization of the various activities and alleviates the chance of postponement. This prioritization can only take place when it is clearly indicated why certain maintenance activities should be conducted. In some occasions it is inevitable that maintenance is procrastinated. In such cases, the factor that causes a maintenance activity to be postponed or not, depends on the underpinning documents that indicate the pavement state.

3.3.5 Diagram Validation

The interviews were held separately and in some occasions there were some contradictories. Furthermore, although the interviews were recorded and directly transcribed, to put the narratives in full context, it is inevitable that there are deficiencies or misinterpretations. Therefore, the interview respondents were inquired to review the results and to provide feedback where necessary, for validation purposes. This feedback loop proved to be fruitful for the validity and the completeness of the diagram.

3.4 Chapter Conclusion

Four interviews were held with both Schiphol and Heijmans insiders, which provided a clear picture of how the MJOP is conceived and the involved parties. More importantly, it shed light on the reasons why pavement maintenance is deferred. The reasons are primarily the limited financial resources and the operational restrictions. The former can be the cause of other projects or a business cycle contraction (e.g. the Covid-19 recession). This reflects that deferred maintenance can be caused by unpredictable and external factors. In addition, it became evident that some pavement maintenance projects were deliberately postponed, because of a knock-on effect of other projects. Finally, there are other external factors that should not be forgotten. For example, Schiphol has many powerful stakeholders with different perceptions. A stakeholder like the municipality or the ministry may hamper the execution of a new pavement maintenance project, by denying a construction permit or by demanding a different project for safety reasons, like one of the respondents addressed.

The enumerated rationales for deferring pavement maintenance are very diverse and provoked by different stakeholders. For the majority of the projects, it is possible to prevent the postponement of pavement maintenance. Unfortunately, this is not valid for all cases. For example, when there is a financial downturn, the aviation industry is disproportionately affected. In such cases, deferring pavement maintenance has become a strategy to quickly reduce the budget deficits. Thus again, not all deferments can be pre-empted.

Chapter 4

Analysis of Pavement Failures

As Schiphol decides to defer pavement maintenance, the taxiway and runway pavement will persist to deteriorate. A conceivable consequence is that the number of pavement failures will incline. If the number of pavement failures will proliferate, the disturbance that the airport operation incurs will aggravate, because these pavement failures requires unplanned maintenance. Consequently, taxiway or runway sections will be blocked, which leads to traffic detour and additional taxi time. The latter can be quantified in terms of costs, as various studies have addressed the costs of traffic delay [31]. However, to evaluate this, it is of essence to first pose the question whether deferred pavement maintenance actually results in an increase in pavement failures. To respond to this question, it will be investigated whether pavement failures can be attributed to the age of an asphalt section. This is done because deferring pavement maintenance de facto means that the pavement will become older than initially planned. Therefore, by introducing this time-dependent variable, the consequences of deferred maintenance can be evaluated. In a later stadium, additional dependent variables will be added to the analysis, because Section 2.1.5 showed that other variables exist, that can either can either amplify or diminish the associated probability of pavement failures. The additional parameters that will be included are variables pertaining to the traffic intensity, aircraft speed, pavement foundation and type of section (e.g. junction, bay or runway). These select variables were chosen prudently, as restrictions in both time and data availability are encountered. Through the literature research, these variables seem to be most relevant and feasible to investigate.

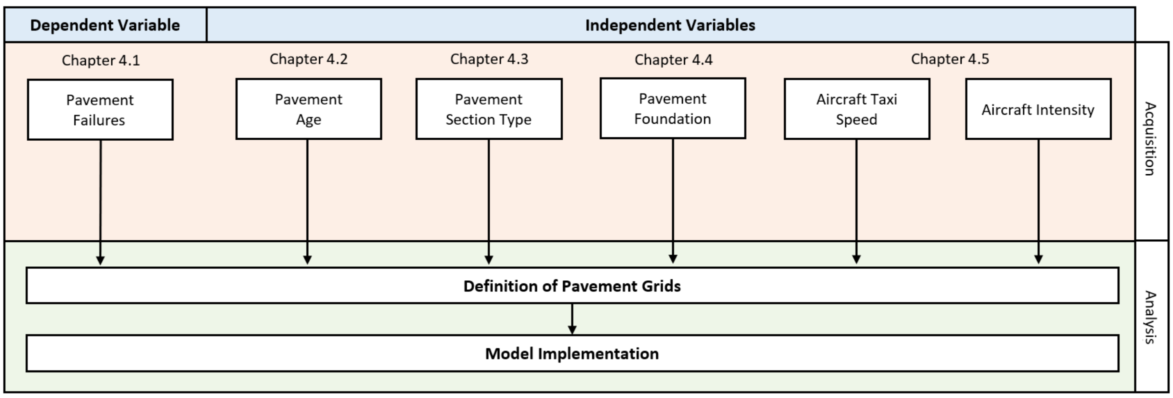


Fig. 4.1. Data Acquisition and Analysis Process Framework.

As this is a vast chapter, comprising of many elements, a framework of this chapter has been created for readability purposes, see Fig. 4.1. As one can see, this chapter follows a strict sequence with two main phases (i.e. data acquisition and data analysis). The first phase can be further decomposed into the acquisition of details pertaining to the dependent variables and the independent variables. The latter is more complex, as it entails different independent variables. Therefore it was decided to segregate each variable, in the data acquisition phase, into a separate subchapter. After the data has been acquired for the entire airport, the entire pavement area will be divided into smaller grids with a comparable size. The details of the aforementioned variables will then be embedded into the smaller grids. Consequently, computations will be made to determine the value of each variable for the given grid. These attributes are unique characteristics for each grid and conveniences the data analysis.

4.1 Pavement Failure Data

4.1.1 Pavement Failure Definition

Section 2.1.2 indicated that there is no universal definition of a pavement failure. However, to ensure consistency in this research, it is essential to have one standard definition of a pavement failure, before commencing the analysis on pavement failure related data. Therefore, for establishing a pavement failure definition, the pertinent key features of the UAC contractual arrangements must be explained in a nutshell. In this contract it is specified that Heijmans is responsible for the entire process of "rectifying a failure". This implies, contracting, securing, solving, controlling and administering the failure report by Schiphol. This must take place within the predefined norms as specified in the "Verification-matrix Maintenance Parcel one". According to this matrix, the runway and taxiway pavements have the function to carry airplanes, they are characterized by a very high criticality and a pavement failure is explicitly defined as an (local) event where the particular pavement has a PCI score of below 55 [-]. The corresponding technical norms stipulate that during unplanned maintenance, the available time for securing the area, is less than an hour. The available time to conceive a repair plan is less than four hours and in 80% of these events the functional repair must take place within eight hours. In the remaining 20%, the available time for the functional repair must be conform the repair plan. To summarize, the definition of a pavement failure for this analysis is an observed pavement distress that is significant enough to disturb the operation to some extent and causes the PCI score to locally drop below 55. In the status quo, the distresses that are reported, predominantly consist of functional distresses on taxiway and runway pavements. These are mainly cracks, potholes and raveling, that are locally affecting the PCI value. Furthermore, in some occasions it may encompass asphalt around manhole covers or cables that are damaged.

4.1.2 Data Acquisition

In order to conduct a data analysis, the data pertaining to the pavement failures must first be collected and processed. After the acquisition of the civil technical malfunction data, it was necessary to filter the data, as it encompasses all civil technical malfunctions for Parcel one, but not all were pavement related failures. Fig. 4.2 depicts a decomposition of all the reported malfunctions. It also highlights what data from this malfunction data set is relevant and which should be eradicated. Furthermore, to comprehend what a pavement failure on a taxiway or runway looks like, refer to the illustrations of pavement failures in Appendix C.

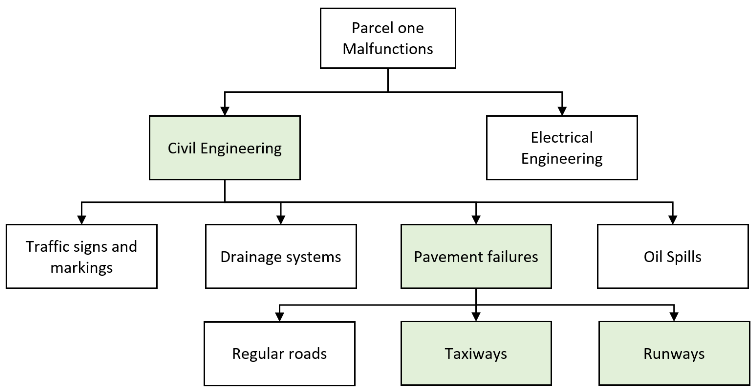


Fig. 4.2. Malfunction Data Decomposition.

4.1.3 Data Accuracy Enhancement

The data between April 2019 and February 2020 were already recorded visually. However, pavement failures in preceding periods were not recorded this rigorously (2011-2019), but at least there is a database that qualitatively indicates the location where the failure manifested. To exemplify, they are specified in the following manner: *Taxiway B, in the vicinity of exit N5, hole in the asphalt, 5 cm depth and 20 cm in diameter*. This qualitative description of the location can be converted to latitude and longitude coordinates, however the accuracy will be compromised since it boils down to proper judgment, which is inherently prone to interpretation errors.

To enhance the accuracy of the pavement failure data, supporting documents, like permit requests, work order documents, declaration forms and on-site images were examined to pinpoint the exact location. Despite the best efforts to obtain accurate data, it should be remarked that there are still minor inconsistencies in the data sets, as for some pavement failures the corresponding documents were absent. After the accuracy of the locations of where the pavement failures occurred was improved, they were illustrated in GIS (for an overview refer to Fig. 4.3). It depicts all the locations where a pavement failure has occurred in the past years.

[redacted]

Fig. 4.3. Pavement Failures at Schiphol.

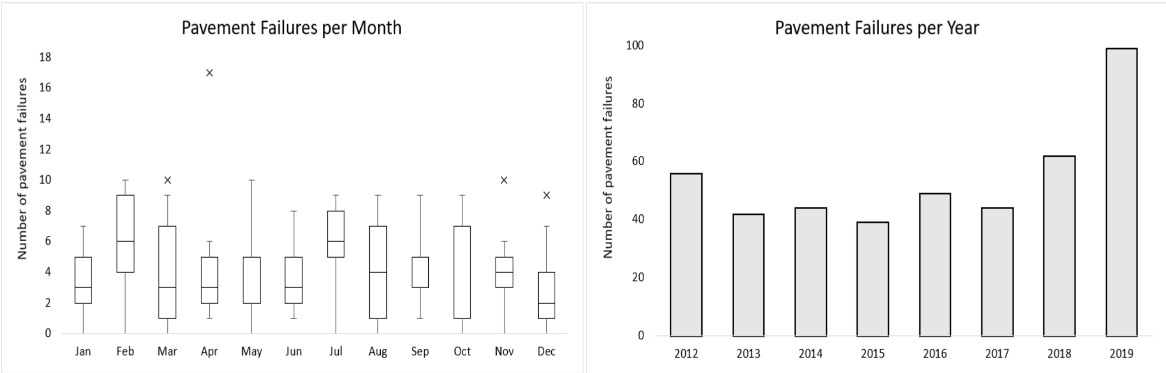
4.1.4 Descriptive Statistics

After the unessential data was eradicated from the data set, 403 pavement failures remained from a time span of approximately ten years. Each of them included several attributes, among others, the moment of reporting and the description of the pavement failure.

At first glance, Fig. 4.3 shows that the pavement failures are arbitrary distributed. However, upon closer examination, it becomes evident that certain areas are more prone to pavement failures. For instance, the runways only show a small amount of failures, while the majority of the total pavement area consists of runway pavements. Conversely, one can observe that more pavement failures seem to emerge in the vicinity of the aprons, namely at the bays. This observation is aligned with underpinning literature from Federal Aviation Agency [19], which has pinpointed certain "critical" areas. These areas a subject to higher adverse loading's, that is provoked by, for example, still standing or slow traveling traffic. However, before conclusions are prematurely drawn, it is necessary to further investigate the observations.

To continue, descriptive statistics was firstly performed before moving on to inferential statistics. The former intends to describe the basic features of the data. It yields simple summaries about the sample and the measures, moreover, it can be checked whether the data is correct and as anticipated [52]. Upon inspection of the results in Fig. 4.4, it becomes evident that there are irregularities. First of all, Fig. 4.4a shows that the pavement failures are depicted as a function of time in months. Instead of showing the total pavement failures per month, it was illustrated with box plots to show the variances. One can observe that an pronounced pattern remains absent, with the exception for February. Furthermore, for April one can see a large variance which is caused by an outlier from 2019.

Furthermore, it is also notable that the number of failures in 2019 is nearly double the amount of preceding years. To seek an explanation for this phenomenon, the data set was examined again and it was found that some pavement failures in the preceding years were not included in the analysis. This was due to the fact that the pavement failures, that could not be immediately remedied due to the lack of equipment, were classified differently. After the number of pavement failures was revised, the number of recorded failures became 453. Despite that the number of pavement failures before 2019 increased moderately and narrowed down the standard deviation in the sample, it still could not get close to the number of recordings in 2019. A possible explanation to justify this phenomenon is arguably the performance based contract for Parcel one that commenced in 2019. Before this period, the zero measurements of the assets had to be measured. Hence the amount of maintenance was decreased following that period, which conceivably led to an increase in failures.



(a) Pavement Failures Boxplots. **(b)** Pavement Failures Histogram.

Fig. 4.4. Descriptive Statistics of Pavement Failures.

4.2 Pavement Layer Age

In addition to data pertaining to pavement failures, also details regarding the pavement age were acquired. The underlying incentive to gather this information is that the number of deferments is not large enough (as shown in Section 3.1), because large maintenance is not conducted at excessive intervals. This lack of data makes finding direct correlations between deferred pavement maintenance and the number of pavement failures cumbersome. A more suitable analysis within the data constraints is to perform this analysis for the pavement age and the number of pavement failures that have manifested. To allow this analysis, the age of the pavement at Schiphol needs to be evaluated.

[redacted]

Fig. 4.5. Pavement Age per Section.

From organizational documents the age of each pavement section was retrieved. Consequently, each pavement section and the corresponding age was added to the GIS file with the pavement failures. In essence, over 200 different pavement sections were identified, varying from small to large sections (take notice that some sections overlap). To observe the pavement age, see Fig. 4.5. As the records only date back to approximately 2003, layers that were paved before 2003 are simply denoted as "2002". Furthermore, it must be mentioned that this figure merely represents the asphalt layers up until 2019. According to the MJOP, maintenance will be conducted on the Polderbaan and Aalsmeerbaan in, respectively, 2021 and 2022. Hence, this figure is subject to change from year to year.

Despite that the vast majority of the pavement layers are made from asphalt, at some particular sections the pavement layer was produced with concrete. Notable sections where concrete was used, is for example the head of some runways, where aircraft stand still before departure. These concrete sections are depicted in white, allowing one to easily discern between asphalt and concrete layers. The properties of concrete sections are different and have a greater longevity than asphalt. Therefore, it can be interesting to analyze how different types of pavement lead to pavement failures. However, there are no records of the age of concrete sections, as concrete pavements can last for up to 50 years or longer [53]. Due to this lack of data, it is unfeasible to analyze whether concrete sections are more robust against pavement failures. On the other hand, the number of pavement failures that occurred on a concrete pavement can be computed. Through GIS, it was found that approximately 5.5% of the total pavement at Parcel one, consists of concrete. Furthermore, it was found that from all the pavement failures between 2011-2019, approximately 10% manifested on concrete sections. This finding seems disproportional, however as mentioned before, concrete sections have a greater longevity and these sections are most likely much older than the asphalt sections. For example, in Section 3.1 it was addressed that MJOP project GOH 157, involving a concrete pavement section, was deferred various times. This may be one of the reasons why this high number of pavement failures was observed.

4.3 Pavement Section Categories

Pavement failures cannot solely be attributed to the pavement age, for instance Kazda and Caves [3] stressed that there can be various underlying factors that may affect the asphalt properties. To address this, it was decided to also include other factors to analyze whether individual or a combination of factors can contribute significantly to the emergence of pavement failures.

Fig. 4.6. Identified Pavement Sections.

According to Hunsucker and Meade [54], more shear stress is exerted on non-tangent segments of pavements such as curves and steep grades. In addition, in certain areas, the aircraft load repetition and the aircraft taxi speed are different. This is also a factor that justifies why the rate of degradation fluctuates for different pavements sections [19]. Therefore it was decided to also consider a spatial independent variable in the analysis, in which taxiway junctions, straight taxiway sections, bay areas, runway exits and runways are differentiated. These sections are exhibited with different colors in Fig. 4.6. Respectively, they are marked in light blue, purple, red, yellow and dark blue. By discerning between different types of sections, it can be analyzed whether this has an influence on the pavement failures.

4.4 Pavement Foundation Characteristics

Literature has often addressed that the pavement foundation, consisting of the base course, sub-base and sub-grade, affects the overall durability of a pavement [20]. And since the pavement foundation is different from location to location, it could change the associated risk of pavement failures from place to place. Hence, it is interesting to inquire into the relationship between pavement failures and the composition of the foundation. Therefore information regarding the pavement foundation was assembled.

4.4.1 Schiphol Pavement Composition

Upon investigation, it was found that two types of records pertaining to the pavement foundation were at disposal. One record stems from 1956, while the most recent record originates from 1983. The latter is depicted in Fig. 4.7 and reveals the composition of the pavement foundation across various areas. However, it is worth noting that back in the time when these records were conceived, neither the Bravo taxiway system, the Polderbaan runway, Hotel platform and Golf pier were yet built. Hence, the latest (available) data is merely partially complete.

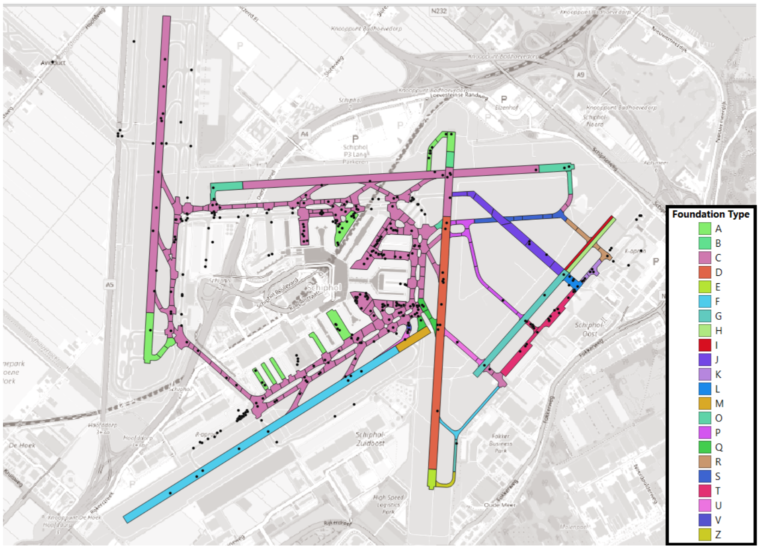


Fig. 4.7. Foundation Types Across Schiphol.

Upon inspection of Fig. 4.7, it becomes evident that there is a great diversity in pavement foundation types at Schiphol. In total, 26 different combinations of foundation composition were identified (not all shown in the figure). Especially the number of foundation types at Schiphol-Oost is peculiar, because there are around 20 different types at a relatively small area. An explanation for this, is that over half a century ago, the terminals of Schiphol used to be on the location where Schiphol-Oost is currently located. In that period, the Aalsmeerbaan and Oostbaan were already operative, this justifies why different sections of these runways have different foundation compositions. Possibly back then, when the pavement foundation was erected, there was no standard concerning the foundation. These layers were possibly paved in different periods, and each time innovations were applied. Hence each time, a different foundation was created. In addition, the purpose of a given section, be it a runway or a bay, is possibly also a driving factor determining the foundation composition. When solely inspecting the areas west of the Aalsmeerbaan, one may notice that there is much more uniformity when it concerns the foundation composition. For instance, the majority of the runway and taxiway foundations are built from type C, on the other hand, type A is predominantly used for the aprons and for some areas of the bays. A cross section view of some foundation types is depicted in Fig. 4.8.

It depicts that foundation type C consists of 28 cm of asphalt, whereas types A and O are primarily made of concrete. The former consists of a mix between asphalt and concrete and is used for the aprons, some bay areas and the displaced thresholds, the latter on the other hand, consists of 85 cm of concrete and is solely used for the displaced thresholds. Based on the location of the pavement section, it can be partly derived how the pavement foundation is composed. Despite that the information about pavement foundations is readily available, it is incomplete and the number of foundation types is too excessive, to be useful for investigating the relationship between pavement failures and foundation type. For this reason, a different approach was taken, namely the use of pavement surface deflection measurements. In the next subsection, this pavement foundation indicator will be further elaborated.

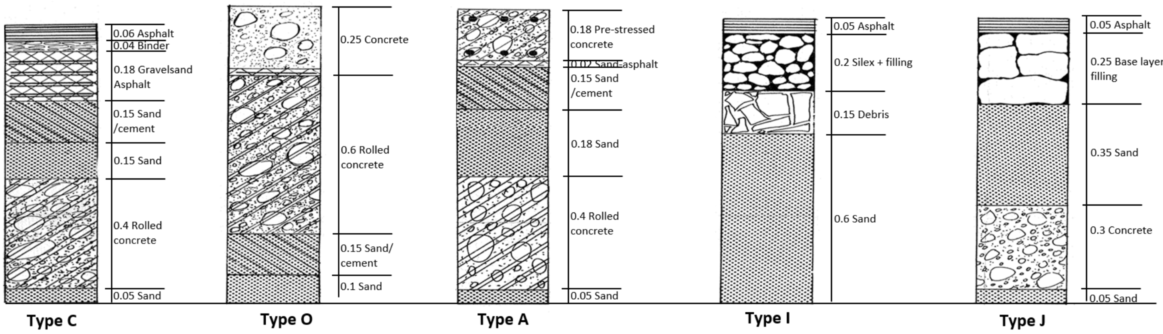


Fig. 4.8. Schiphol Pavement Foundation Composition.

4.4.2 Schiphol's Pavement Surface Deflection

An introduction of the pavement surface deflection was given in Section 2.2.4, therefore this section will only proceed with the measurement results. In total, the assembled data consists of 6000 measurements, which were recorded in different periods. The entire data set contains measurement from all areas, with the exception of DE bay and the A platform. To get a notion of the range of the measurements and how they are distributed, Fig. 4.9 was created. This scatter- and boxplot graph distinguishes between four types of measurements, based on the measurement location. This distinction was earlier introduced, however the only exception this time is that the measurements for runways and runway exits are merged. In general, the graph shows that the recorded measurements are largely dispersed. This is also the reason why this graph uses a logarithmic scale with base 2. Furthermore, take notice that the boxplot excludes outliers, which are measurements either greater than $Q_3 + 1.5 * IQR$ or lower than $Q_1 - 1.5 * IQR$.

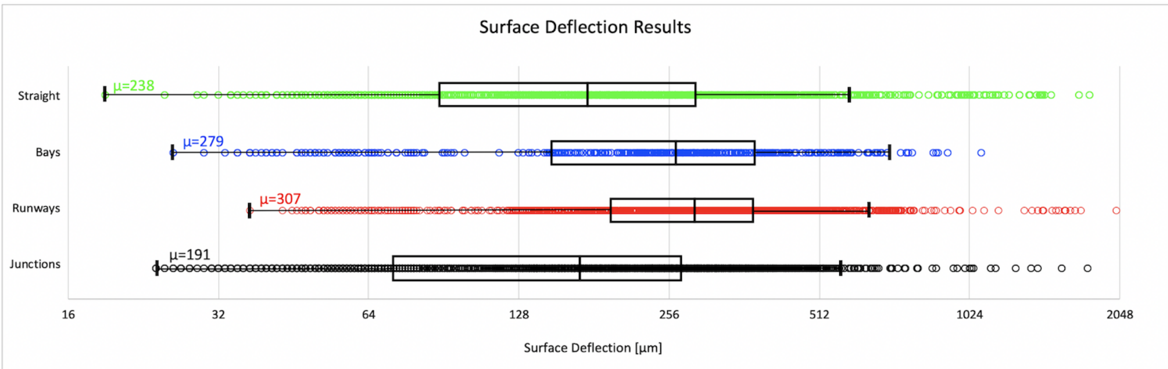


Fig. 4.9. Pavement Surface Deflection Results of Schiphol.

The lowest recorded measurements are close to 20 μm, whereas the highest recordings are up to 2050 μm, which is equivalent to 2.05 mm. Regarding the extent of dispersion, they are more or less equal for all four types of measurements. Conversely, the medians seem to have larger differences. The same holds true for the averages. For all cases the averages are higher than the medians, since the data is right-skewed. Or in other words, there are major outliers in the high end of the distribution that are pushing the averages towards the right. The outliers depicted in Fig. 4.9, may have different causes. For instance, pavement sections with distresses are impaired and will therefore show a higher surface deflection [55, 56]. However, as distresses are locally, only a limited number of measurement should exhibit high deflections. Take the measurements for the runways as an example. There is one measurement secluded from the others, this measurement is possibly recorded at a pavement distress. On the other hand, there is a cluster of measurements between 1500-1700 μm. This is presumably the result of a compromised foundation, because samples are often taken every

5-10 meters. Hence, if there are multiple high deflections, it would concern a substantial area, which is probably not caused by distresses as they remain relatively local.

A compromised foundation however, is not necessarily the result of prolonged (heavy) traffic loading, it could also be provoked by a nonlinear behavior of the base materials or discontinuities [57]. For example, when a rainwater drainage system, underneath the foundation, must be replaced or repaired, one must excavate through the foundation. Afterwards, the foundation must be reconstructed. This could lead to a different foundation composition, which may cause a sudden increase in surface deflection. Especially the measurements near joints or edges can provoke larger discrepancies in the surface deflection than testing at interior portions of the pavement [58].

4.5 Traffic Intensity and Aircraft Speed

Currently, there is only information available about how the airport movements are distributed among the runways and the bays. More importantly, information pertaining to how the traffic moves from the former to the latter and vice versa is unknown. In addition, it is unspecified at what taxi speed the traffic operates, because airport and aviation authorities have not clearly defined a guideline regarding taxi speeds. For instance, the FAA recommends to "maintain an appropriate taxi speed" [59]. On the other hand, aircraft manufacturer Boeing, has specified in a flight crew training manual that "a normal taxi speed is approximately 20 kts, adjusted for conditions. On long straight taxi routes, speeds up to 30 kts are acceptable. When approaching a turn, the speed should be slowed to an appropriate speed for conditions. On a dry surface, use approximately 10 kts for turn angles" [60]. So in essence, there are no guidelines for taxi speeds and it partly comes down to judicious use of the taxiway, while considering the conditions. Since the speed may vary for circumstances and location (e.g. dry/wet surface, straight/turn taxi routes) and different airports may impose different restrictions, it is cumbersome to derive the taxi speed from literature. To reveal information about the traffic intensity and the taxiing speed at various taxiway sections, it was opted to assemble aircraft transponder data from Schiphol Airport. This data yields valuable information for the statistical analysis, but could also be exploited for other purposes.

4.5.1 Aircraft Transponder Data

Aircraft transponder data was retrieved from Schiphol Airport, which receives transponder data through transmitted broadcasts from an aircraft or a ground vehicle. These vehicles periodically transmit their state vector through the Automatic Dependent Surveillance Broadcast (ADS-B) [61]. Such broadcasts are transmitted at an interval of one second, with details pertaining to the horizontal and vertical position in GPS coordinates, the horizontal velocity and call sign of the aircraft. This type of data has a plethora of uses, for instance, the FAA and the NASA are currently investigating the suitability of this technology to support applications in the airport surface environment [61]. However, one must reckon with the fact that the transponder of an aircraft is located near the cockpit. Thus the GPS coordinates do not depict the location where the undercarriage is touching the tarmac.

As aircraft broadcast every second, the amount of accrued data proliferates over time. For instance, at any moment in time during operational hours, there are between 75 to 150 vehicles equipped with ADS-Bs in the vicinity of Schiphol. In total, over two years of ADS-B data is available at Heijmans. However, as one can imagine, this concerns a tremendous amount of data (i.e. 1400 million data points). Therefore it was decided to only consider one month of flight data, as a larger data file would take a significant amount of time to render. To mitigate bias in the data file, it was opted to extract flight data from various periods. As the runway use is predominantly based on the wind conditions. Hence, if the wind direction remains consistent for a prolonged period, there will not be much variation in runway use. If by chance the data set will cover such a period, it will show that certain taxiways are used more frequently, whilst it does not provide a representative view of the average operation. Therefore the data will be extracted from different periods, to eliminate the chance on bias. The selected periods for the flight data are the first two weeks of February 2018 and the first two weeks of April 2018.

4.5.2 Aircraft Transponder Data Preprocessing

The extracted data merely concerns "raw" data, which also entails unfavorable information. Hence, the data sets needed pre-processing. To see the process of transforming raw data into an understandable format, refer to Fig. 4.10. Essentially, this workflow commenced with the extraction of 500 files that contained the raw data. As each file was merely holding a fraction of the total information for approximately 30 days, they had to be consolidated into one single data file through Python. However, as indicated previously, the consolidated data file also contained information, which was unnecessary for the statistical analysis. Therefore the data had to be orchestrated by eradicating certain information. Unnecessary information entails broadcasts from cars, vans, tow trucks and regular trucks. Since the vast majority of the data is produced by these vehicles, the consolidated data file was brought back to 23.3 million data points by eliminating these broadcasts.

Succeeding the first round of pre-processing, the data file was still immense in size. Hence, additional filters were applied. These included filters that eradicated data points with a speed attribute of smaller than "1" and larger than "25" m/s. The rationale for this decision is that often the transponder is still or is already active when the aircraft is still or already stationary. Besides, aircraft with a speed larger than 25 are already on the runway, hence they were not of interest. Furthermore, also data points that were broadcasted from more than two kilometers away from Schiphol, were eradicated by filtering on GPS coordinates.

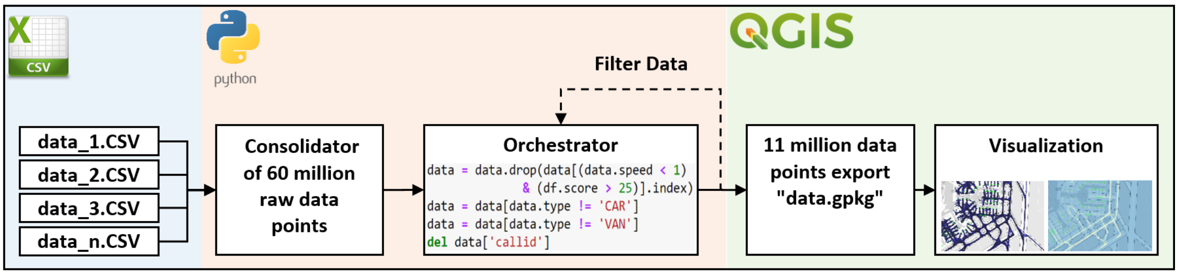


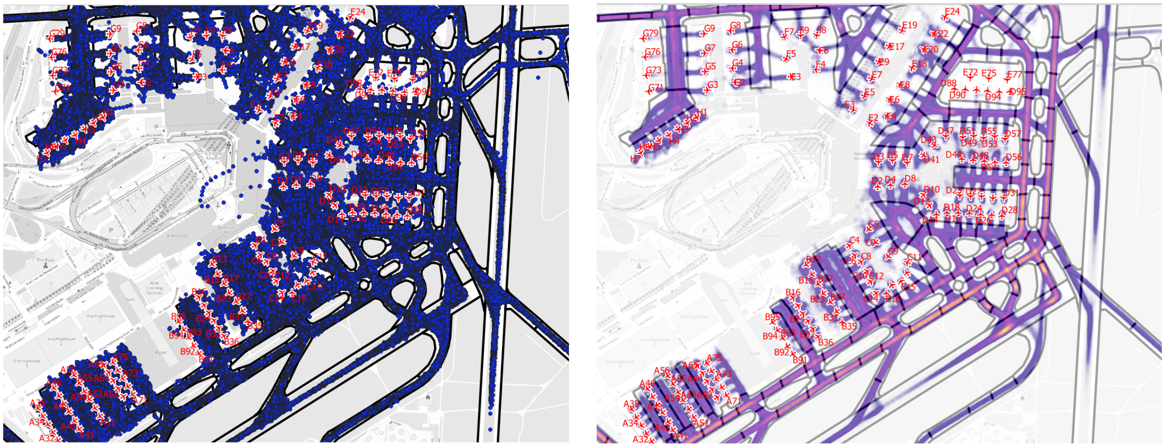
Fig. 4.10. Process Flow of Data Manipulation.

4.5.3 Visualization of Aircraft Transponder Data

Ultimately, the preprocessed data file with 11 million data points was exported to QGIS, due to its merits pertaining to geographical analysis features. In this environment, every data point was projected on a map of Schiphol based on the longitude and latitude coordinates (see Fig. 4.11a). Despite the preprocessing, the data was still difficult to render and analyze, due to its sheer size. Furthermore, the extent of data would simply make the points overlap, which makes a direct analysis on the data unviable. Therefore, an alternative approach was taken, which was to transform the data points into a heatmap. The latter uses a color-coding scheme to visualize the point density, which is shown in Fig. 4.11b. For a heatmap representing the entirety of Schiphol, see Appendix D.

The heatmap gives a clear overview of where most of the data points are accumulated on Schiphol. However, it is extremely important to realize that one cannot directly deduce from this heatmap where most of the aircraft will pass. This is because the data points are dependent on the speed at which the aircraft are traveling. For instance, the broadcasts from a fast traveling aircraft are more dispersed than the broadcasts from a motionless or slow traveling aircraft. This can be illustrated with the Polderbaan (36L) as an example (see Appendix D). The heatmap shows that entrance Victor 4 and the head of the Polderbaan glow like a light bulb. However, at approximately 200 meters from the head, the color turns into purple, indicating a lower density of data points. The number of traffic passing Victor 4, the head of the Polderbaan and 200 meters from the head is identical, but due to the speed of the aircraft, the number of broadcasts per m^2 diminishes rapidly. Hence, one should be careful and also consider the speed of the aircraft, when drawing inferences from the heatmap. A more representative overview is a choropleth that reckons with the aircraft speed.

Since the aircraft speed and the number of broadcasts in a specific area are dependent, the number of broadcasts per section can be normalized by accounting for speed. To illustrate this notion, see Fig. 4.12. It shows two sections of a runway, in which broadcasts are transmitted. The runway at the top is split up in two smaller segments. In the left segment, the aircraft would travel at a speed



(a) Projected Data Points. **(b)** Heatmap of Data Points.

Fig. 4.11. Visualizing Transponder Data.

of 20 m/s and the number of broadcasts would be equal to 60. Conversely, in the right segment, the aircraft travel at a speed of 40 m/s. Because the aircraft would travel quicker, the transmitted broadcasts are sparser and hence a smaller number of broadcasts will be recorded. Albeit, the number of aircraft traversing through both sections is equal, due to their different speeds the data would show otherwise. To account for that, the average speed per section was determined. Thereafter, the speed was normalized to a reference speed and this multiplier was applied on the number of points in a given section. For example, in Fig. 4.12, the left top section was normalized to a speed of 40 m/s. This would provide a multiplier of 0.5 and by applying this on the number of broadcasts, it will decrease to 30. The latter can be seen in the bottom section of Fig. 4.12.

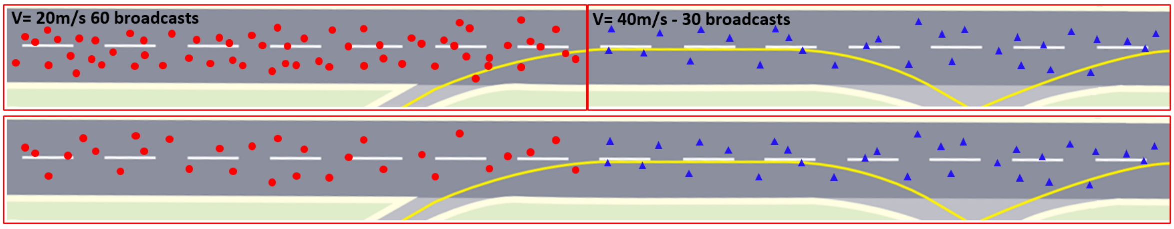


Fig. 4.12. Data Points Normalization.

By following the same notion, a choropleth was created with the earlier defined sections of Fig. 4.6. For each grid in this map, the total area size, the average speed and the number of data points were computed. By dividing the number of points per grid by the total area m^2, the point density points/m^2 was computed. This value was then normalized by considering the speed in the given grid. Thereafter, the point density was converted to aircraft numbers by using a reference field. For example, the traffic numbers per runway is known, hence by using proportional tables, the traffic numbers for unknown taxiways can be determined. The results are shown in Fig. 4.13.

The choropleth gives a better overview of the traffic intensity than the heatmap depicted in Appendix D, as the former has eliminated the speed factor in the data points. Through the choropleth it becomes immediately apparent that certain sections are used more extensively than other sections. For example, there are various routes leading from the bays to the Polderbaan. The first option at disposal is either the use of Taxiway Alpha or Bravo (recall that they are respectively for clockwise and counterclockwise directions). Both taxiways lead to taxiway Yankee, Whiskey and Zulu. According to Fig. 4.13, taxiway Yankee is the least used taxiway to the Polderbaan, whereas taxiway Whiskey is the most prevalent route. Furthermore, it is also noticeable that taxiway Quebec and Victor are extensively used. The fact that taxiway Quebec is used this extensively, is because it is a bidirectional taxiway. Taxiway Alpha and Bravo on the other hand, can relieve each other.

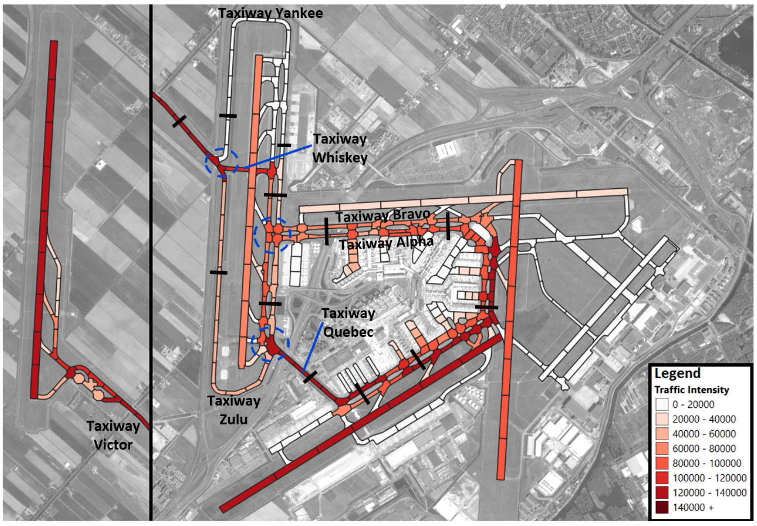


Fig. 4.13. Choropleth Showing the Traffic Intensity.

4.5.4 Traffic Intensity for the Pavement Sections

Traffic Intensity at Taxiways

To give a better indication of where most of the airplanes pass, see Fig. 4.14. In essence, it shows that the most used taxiways are taxiway Quebec and Victor. At the other limit of the dimension, taxiway Yankee is least often used.

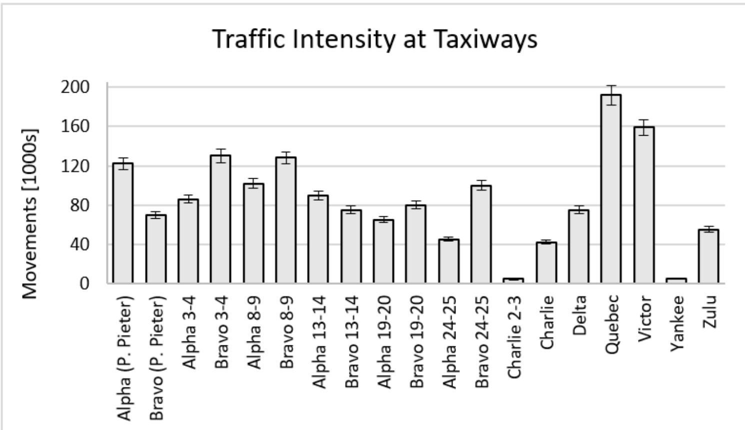


Fig. 4.14. Traffic Intensity at Certain Taxiways.

Furthermore, it becomes evident that about 59.8% of the total traffic from/to the Polderbaan or Zwanenburgbaan uses taxiway Quebec to navigate between the bays and these runways. This is by far the most used route to the aforementioned runways. The fact that Quebec is used most frequently is because it is bidirectional and due to the location of the bays. As Table 4.2 showed, around 60% of all the airport traffic originates from the bays A, B, BC, CD and D, which that are located on the south side of Schiphol and hence closer to taxiway Quebec. The remainder of the traffic that uses the Polderbaan or Zwanenburgbaan, uses taxiway Alpha (23.2%) and taxiway Bravo (17%). Recall that the former is predominantly used for clockwise directions and the latter for anticlockwise directions.

To analyze how the traffic splits up at the end of each of the taxiways, gates have been created to solely analyze how the traffic is distributed at junctions. The results of this computation are depicted in Fig. 4.15. The junction on the left, shows how the traffic is distributed at taxiway Quebec. In essence, the majority of the traffic (35.2%) comes from taxiway Bravo, which is most likely landing traffic coming from the Polderbaan and the Zwanenburgbaan. Then 29.7% of the traffic coming from taxiway Quebec, turns directly to the Zwanenburgbaan for take-off. Another 20.3% either comes or goes to the Polderbaan, via taxiway Zulu (bidirectional taxiway). The remaining 14.8% travels north via taxiway Alpha, most likely this concerns traffic that will depart from the Polderbaan.

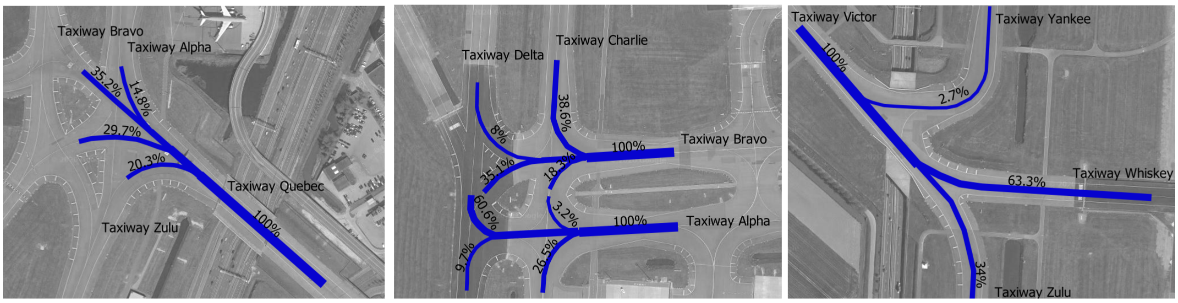


Fig. 4.15. Traffic Distributions at Junctions.

Then pertaining to taxiway Alpha, it can be seen that about 60% of the traffic, stems from either the rapid exit taxiway (W6) of the Zwanenburgbaan or comes from the Polderbaan, via taxiway Whiskey. Another significant portion of the traffic comes from the south (26.5%), which is for the most part traffic from the rapid exit taxiways W7 and W8 and to a small extent from taxiway Zulu. Then regarding taxiway Bravo, about 39% of the traffic goes directly north, which are primarily taking off from the Polderbaan. Lastly, 35% moves to the south, which is either traffic that departs from the Zwanenburgbaan or the Polderbaan (via taxiway Zulu).

Then finally, the junction that leads to the most used runway, the Polderbaan, with about 158,900 movements on a yearly basis. In essence, it can be inferred that taxiway Whiskey is by far the most important taxiway for traffic leading to or coming from the Polderbaan (63.3%), which is good for annually about 100,600 movements. The second most used taxiway is taxiway Zulu, which is utilized by about 54,000 movements. Lastly, taxiway Yankee, is only used by 2.7% of the traffic. So in essence, the most catastrophic location where a pavement failure can occur, in terms of operational impact, is at either taxiway Victor or taxiway Whiskey. If it would emerge at taxiway Victor, the entire Polderbaan would be out of operation, which actually occurred in 2018. Despite the absence of conclusive evidence, indicating that the pavement failure was provoked by deferred maintenance, this event does demonstrate the magnitude of disorder which one single pavement failure can cause.

Altogether, the choropleth and the corresponding details, have demonstrated that when a pavement failure occurs at taxiway Quebec, Whiskey or Victor, it would have a larger operational impact than for other taxiways (e.g. Yankee or Zulu), as more traffic has to divert. Although, these details can be fruitful for many purposes, it did not exactly pinpoint the quantitative operational impact when shut off. Therefore, these details will be used in a later section, wherein a different analysis will be conducted for the sake of determining the varying magnitude of impact of a pavement failure.

Traffic Intensity at Runways

The traffic distribution among runways was derived from Schiphol reports [62, 63]. By retrieving information from one of these studies, Fig. 4.16 was created. It shows the expected average, maximum and minimum expected runway use for 2020, under normal circumstances and average weather [63]. According to reports of predecessors, the forecasted runway use for 2020 bears a strong resemblance to preceding years.

One may infer from Fig. 4.16 that certain runways are used more extensively for landing or take-off than other runways. To find out which runway is used most frequently, information from this figure was extracted to create Table 4.1. This table shows the total traffic volume for each runway, by combining the take-off and landing traffic numbers for both directions. Take notice that this table does not encompass the "other" traffic from Fig. 4.16. Therefore the table is merely showing 496,500 flights, rather than 497,300 flights, hence only 99.84% of the total traffic is taken herein. Nonetheless, it can be inferred that the Polderbaan and Kaagbaan are used most often. These exploitation rates can be justified by the runway preference scheme. On the other hand, the Oostbaan is only sporadically used. This is because the Oostbaan is the shortest runway and therefore not adequate for most aircraft. When the Oostbaan (22) is operative, it is only meant for landing traffic, and in the majority of the cases for (small) general aviation traffic [64]. The occasions wherein this runway is operative,

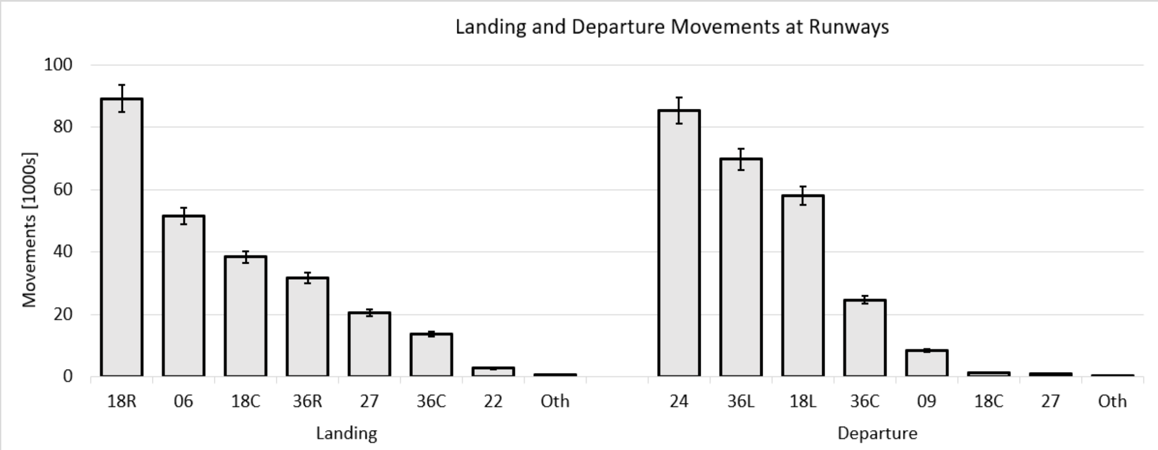


Fig. 4.16. Departure and Landing Movements on Most Used Runways.

is when there is too much southwest wind. Under these circumstances the Polderbaan cannot be used due to crosswinds. Nevertheless, it is highly unfavorable to use the Oostbaan, as the city center of Amsterdam lies in the approach path [64].

Table 4.1. Traffic Volume per Runway.

Runway Name	Traffic Volume	Proportion
Polderbaan (18R-36L)	158,900	32%
Kaagbaan (06-24)	137,000	27.6%
Aalsmeerbaan (18L-36R)	89,700	18%
Zwanenburgbaan (18C-36C)	78,200	15.7%
Buitenveldertbaan (09-27)	30,000	6%
Schiphol Oostbaan(04-22)	2,700	0.5%
Total	496,500	99.84%

As one may have notice, the runways in this section were not always addressed by their names, but with their runway designation. This is due to the fact that the majority of runways at Schiphol airport are bidirectional, with the exception of the Polderbaan and Aalsmeerbaan (see Fig. 5.1). Since Schiphol has a socio-economic function, it has the social duty to mitigate nuisance in adjacent urban areas. Hence the aforementioned runways are restricted to unidirectional traffic. Considering that a runway is usually bidirectional, means that one single runway actually serves the function of two runways, as both directions can be used, albeit not concurrently. Hence, traffic can utilize a runway for two types of maneuvers (i.e. landing and take-off) in two different directions. To prevent confusion and to indicate which runway the pilots must use, runway numbers are used. These numbers are placed as markings at the head of the runway and are established based on the magnetic azimuth of the runway's heading in decadegrees. However, as runway systems can get increasingly complicated, it is necessary to differentiate between parallel runways with letters. Parallel runways are denoted with Left (L), right (R), or center (C). For instance, the Zwanenburgbaan can be either used in the direction of 180 or 360 degrees for landing or take-off. As the Zwanenburgbaan is in the center of the parallel runway series (Polderbaan-Zwanenburgbaan-Aalsmeerbaan), it is called 18C or 36C. For more details regarding markings, please refer to FAA.

Traffic Intensity at Bays and Runway Exits

In the preceding subsection, the traffic volume per runway was briefly analyzed for Schiphol. This analysis can be extended, by analyzing the traffic volume per runway entrance/exit and the bays. For instance, the details in Fig. 4.16 depict the number of origin or destination trips. It shows that annually 90,000 and 70,000 aircraft land and take-off respectively, on and from the Polderbaan (18R-36L). By consolidating this information with the details about the exits and entrances taken from To70 [62], it can be determined which exits or entrances, or a combination of both, are most used. It is noteworthy that this data was registered in 2016 [62]. However, in the recent years, the number of operations has maintained consistent. Therefore, this data was generalized. Furthermore, in a different study, the proportion that uses a given bay was analyzed [65]. Take notice, that the level of detail is not at gate level, as this would considerably complicate the data. By combining the traffic volume information for the runway exits/entrances taken and for the bays, it can be determined where the 90,000 aircraft (that originate from the Polderbaan) and the 70,000 aircraft (heading to the Polderbaan), are destined to or originate from. In the same manner this can be replicated for other runways. To display this information, an origin-destination matrix was created.

O/D matrix			Destination												Σ
			Bays												
			A	B	BC	CD	D	DE	EF	FG	G	H	R	S	
Origin	Polderbaan	V1	2787	1845	3300	3443	1537	2521	840	1045	615	1824	266	492	20516
		V2	6060	4010	7173	7485	3342	5480	1827	2272	1337	3965	579	1069	44600
		V3	3272	2165	3874	4042	1804	2959	986	1227	722	2141	313	577	24084
		V4	0	0	0	0	0	0	0	0	0	0	0	0	0
Σ			12119	8020	14347	14971	6683	10961	3654	4545	2673	7931	1158	2139	89200

Fig. 4.17. Fraction of the Origin-Destination Matrix.

In Fig. 4.17, a fraction of the comprehensive origin-destination matrix is depicted (see Appendix E for a full overview). In this example overview it is illustrated how the landing traffic on the Polderbaan is distributed among the different exits. It should be underlined that exit "V4" is solely exploited as an entrance. After the aircraft exits the runway, they navigate from the origin zone to its designated bay or destination zone (in transport analyses the origin and destination locations are often denoted as zones). The destination zones, that one can navigate to, are depicted in the horizontal axis. In Fig. 4.17, it is only shown for traffic originating from the Polderbaan how traffic is scattered across the different zones. So essentially, what one can deduce from this matrix is which of the bays handle most of the traffic volume and which of the exits are most important for the runways. With data from the matrix, Table 4.2 was erected. It shows that the most used bays are A, B, CD, DE and GH. Together, they process around 70% of the total traffic.

Table 4.2. Traffic Volume per Bay [65] .

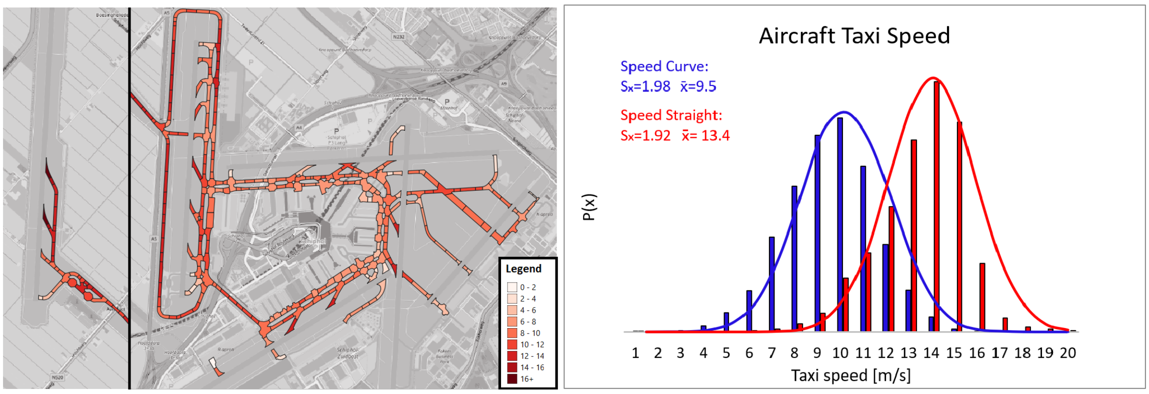
Bay Name	Number of Gates	Traffic Volume	Bay Name	Number of Gates	Traffic Volume
Bay A	27	14%	Bay EF	9	5%
Bay B	11	9%	Bay FG	8	5%
Bay BC	15	16%	Bay GH	15	12%
Bay CD	19	17%	Bay R	7	1%
Bay D	10	7%	Bay S	11	2%
Bay DE	28	12%			

4.5.5 Aircraft Taxiing Speed

The aircraft transponder data also yields the aircraft speed at the moment of transmitting the broadcast. This data was separately analyzed in GIS. In Fig. 4.18a, the average taxi speed per section is depicted. It shows that the average taxi speed at taxiway Alpha and Bravo are lower than for taxiway Quebec, Zulu, Yankee and Victor. Conceivably this is because of the sheer amount of junctions at taxiway Alpha and Bravo. Furthermore, one can observe that the average taxi speed at a curvature taxiway is lower than at straight taxiways. To investigate the difference, a sample size of 250,000 data points was used. This data was processed to a histogram for both types of sections (see Fig. 4.18b).

From the histogram it becomes apparent that the average taxi speed in curvature sections is around 9.5 m/s and for straight sections it is approximately 13.4 m/s. Converting this to knots, yields respectively 18.4 and 26 kts. This shows that the average taxiing speed conforms with the recommendations of the flight crew training manuals. However sporadically, some aircraft would even reach traversing speeds of 20 m/s, which is equivalent to around 40 kts. Then pertaining to the sample standard deviations, for curvature sections, the taxiing speed is slightly more disperse.

In addition to simply examining the taxi speeds across different taxiways, a separate data file involving stationary traffic was created through Python. This involves one month of data, in which over seven million broadcasts from stationary aircraft were recorded. Since all these broadcasts are



(a) Average Taxi Speed Across Sections.

(b) Taxiing Speed Distribution.

Fig. 4.18. Average Taxi Speeds.

transmitted from motionless aircraft, the data can be directly projected on heatmaps without further data corrections or manipulations. In Fig. 4.19, the point density heatmaps, expressed in points/m^2, is depicted for Schiphol central. As anticipated, the majority of the recordings stem from the bay or gate areas. This is not necessarily bad, but since the heatmap is based on the point intensity, an area with a high point density would dominate over areas where the points are sparsely distributed, in which the latter would almost be invisible on the map. By excluding the bay and gate areas, the surrounding taxiway system can be analyzed more thoroughly. Hence, the heatmap in the middle was created.

In essence, the figure in the middle shows that the runway entrances and the head of the runways are dominant. This is due to the fact that most aircraft have to queue before take-off. Furthermore, in some occasions, pilots have to wait for instructions or prepare the aircraft for take-off, while standing on the runway. Hence, many broadcasts from stationary aircraft stem from these areas. By also excluding these areas, the heatmap on the right was created. The latter gives a clear indication of the taxiways with some extent of congestion. This may be insightful for a plethora of things, among others, one may use this to scrutinize the current runway use strategies, and perhaps alter it. Because it is pronouncedly visible from Fig. 4.19, that there is a high level of congestion in the holding area of various runways, for example the Buitenveldert- (09) and Kaagbaan (24). This may have provoked traffic jams in the adjacent taxiways, and may even affect the overall traffic flow on Schiphol. Considering this information, it can be prudent to better distribute traffic to other holding areas of a runway, to alleviate congestion.

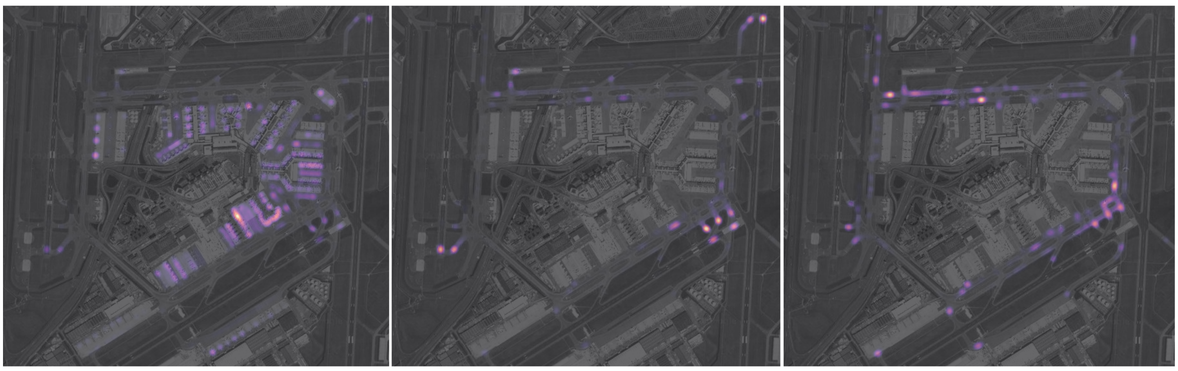


Fig. 4.19. Heatmap of Stationary Traffic.

4.6 Definition of Pavement Grids

Fig. 4.1 depicted that the second phase of this chapter entails the data analysis. And since the data acquisition phase has been finalized, this research can now stress on consolidating the acquired information pertaining to the independent and dependent variables. This has been attained by splitting the entire acreage of 4 km^2 into 328 comparable grids. The number of grids is partly arbitrary, because the entire area had to be divided into comparable grids. Furthermore, the number of grids had to stay in a certain range, because too many grids would make the analysis too complex, while too few, would make it difficult to differentiate the grids based on their attributes. The majority of the grids are comparable in size, with an exception for the runway grids, which are double the size of other grids, since runways are twice the width of taxiways. After the grids were defined, information pertaining to the independent variables from preceding sections were stored as attributes in the grids.

Fig. 4.20. Attributes of the Pavement Grids.

To comprehend how these attributes are embedded in the grids, refer to Fig. 4.20. It shows an arbitrary chosen grid (id=133) with the corresponding attributes. For the runway grid that is paved in 2008, the aircraft speed is relatively high, as one would expect for runways. Furthermore, it is notable that the average surface deflection is relatively high, with a value of 540 μm. Lastly, it is also remarkable that this grid is characterized by a "high" number of stationary traffic. Albeit, counter-intuitive, because aircraft are not supposed to stand still on the runway, it could be justified by the fact that this grid is connected to a runway entrance.

By storing all the acquired information in one single place, one can conveniently compare all of the grids, with respect to all the attributes. More importantly, it helps to analyze how the pavement age influences the number of pavement failures and is meaningful in identifying the locations that are subject to higher failure risks. To explain how each of attributes will be used in the data analysis, refer to Table 4.3. In essence, it provides a short description of the attribute and its corresponding unit of measurement.

Table 4.3. Evaluated Variables for the Data Analysis.

Attributes	Description and Unit of Measurement
Pavement Layer Age	The year in which the asphalt layer was paved is given as a date, it can be easily converted to the layer age. This is a ratio scale, due to its quantitative nature and the fact that the values have a specific order [yr].
Pavement Section Categories	The pavement grids are classified according to their category, which are bays, junctions, runway exits, runways and straight taxiway sections. This is a nominal variable, which has no intrinsic order [categorical data].
Surface Deflection	The used indicator for the pavement foundation are the surface deflection measurements. These are quantitative measurements and follow a ratio scale [μm].
Aircraft Taxi Speed	The aircraft taxi speed is a ratio scale variable, that describes the average speed in the given grid [m/s].
Stationary Aircraft	Stationary aircraft is expressed as an ordinal scale variable, that describes the extent to which the given pavement section is exposed to static loads. Based on the number of stationary data points in the given pavement grid, classes are defined and dummy coded as "None, Low, Moderate and High" [categorical data].
Traffic Intensity	The traffic intensity shows how many aircraft are passing a given section. This is a ratio scale variable [movements/yr].

In addition, the pavement failure details from Section 4.1 were projected on the grids. This yields the option to examine the pavement failures while considering the pavement foundation, type of section, layer age, aircraft speed and traffic intensity. However, as pavement failures have emerged over the years, the layer age should be modified and be time dependent. For example, when a pavement failure occurred in 2018 and the pavement grid was paved in 2003, the corresponding layer age at failure manifestation is 15 years. Ideally, this should also be done for the other variables, by making them time dependent. For example, by deriving the traffic intensity and surface deflection in the years prior to 2018. However, due to the absence of accurate data, this is unfortunately not feasible.

Before, conducting the analysis, it is pivotal to conduct a correlation analysis on the independent variables, as it reveals whether these variables are directly correlated. This will exhibit whether multicollinearity is present, which is detected by a high correlation among predictors. In such cases, one predictor in the model can be predicted by another predictor, this leads to several adverse effects on the estimated coefficients [66]. For example, in a multi regression analysis the notion is to predict the dependent variables with predictors. However, when predictors are correlated, the change of one predictor will not only alter the dependent variable, but also other predictors. By pair-wise testing the variables for correlation, this phenomena can be detected. Upon conducting the analysis it was found that none of the pairs showed a significant correlation. The highest R-square of 16% was found between the aircraft speed and the stationary traffic. This extent of correlation seems plausible and there is a rational explanation. In Section 4.5 the aircraft taxi speeds were derived, however, this was done separately for stationary traffic and moving aircraft. Nonetheless, areas with many broadcasts from stationary aircraft, will push the aircraft taxi speed to the left and hence decrease the average. This is because when aircraft accelerate from zero velocity, it will have a relatively slow speed in the first few seconds. Since the risk of having the multicollinearity problem is when the R-square value approaches 80% to 90%, this is not posing a problem. Hence no variables have to be eradicated to guarantee the models efficacy.

4.7 The Probability of Pavement Failures

This section will emphasize on the analysis of the acquired data, by consolidating all information from the preceding sections. Since the primary objective is to investigate the consequences of deferred maintenance, the pavement failures will be firstly analyzed in the light of the asphalt layer age. This will reveal how older asphalt layers are related to the number of pavement failures. Thereafter, the analysis will be elaborated by introducing the other independent variables to the analysis.

4.7.1 Probability of a Pavement Failure as a Function of Asphalt Age

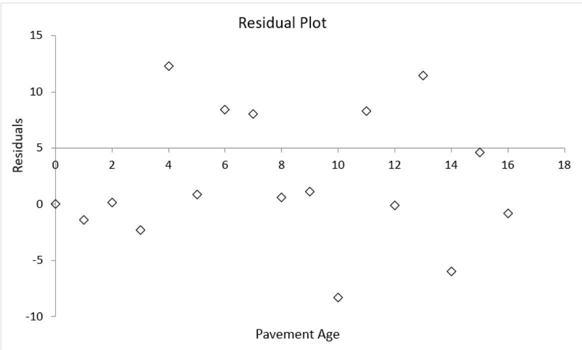
As time passes, the condition of a pavement degrades due to altering properties [45]. Subsequently, the pavement becomes more susceptible to distresses (i.e. pavement failures). To understand how the age of the pavement contributes to pavement failures, they have been analyzed by geographically linking the recorded pavement failures from Fig. 4.3 to the pavement grids and their attributes from Fig. 4.20. By doing so, it can be determined at what pavement age most of the failures occur. For instance, if a pavement failure emerged in 2018 on a pavement erected in 2004, the failure occurred when the pavement was between 14 years old. By repeating this process, information was acquired for every single pavement failure. It is worth noting that this analysis only encompasses pavement failures that have occurred on Parcel one, hence pavement failures on aprons are omitted.

The analysis was conducted for both asphalt and concrete sections within the boundaries of Parcel one. Despite that no details were available pertaining to the age of the latter, it was found that 46 failures emerged on concrete sections (roughly 10% of the total failures). With the information of the remaining failures, Table 4.4 was created. It becomes immediately evident that there are no signs of an equiprobable model, in which all the outcomes are equally probable. Or in other words, it indicates that the likelihood of a pavement failure occurring changes when the pavement age alters, which is as anticipated.

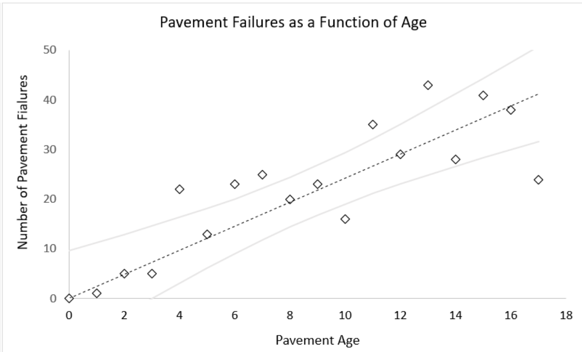
Table 4.4. Pavement Failures as a Function of Pavement Age.

Pavement Age	0-2	3-5	6-8	9-11	12-14	15-17
Frequency	6	40	68	74	100	103
Portion [%]	1.5%	10.2%	17.4%	18.9%	25.6%	26.3%

When examining Table 4.4, it becomes evident that the number of pavement failures gradually increases as the pavement age rises. However, there appears to be a turning point, at which the number of pavement failures stagnates. The observed phenomena seems perversely counter-intuitive, because this would imply that it becomes lucrative, in terms of pavement failures, to deliberately delay maintenance, since the number of pavement failures remains the same as the age progresses. Therefore the data was scrutinized again and it was found that this phenomena was caused by the fact that most of the asphalt layers are replaced at an interval of 15 years. Hence, there is a lower chance for a pavement failure to occur on a pavement which is older than 15 years. Nonetheless, a regression model was applied on the data. However, for the model to fit the regression model, the data must be homoscedastic, which can be tested through residual plots [67]. In principal, Fig. 4.21a shows that the data is randomly dispersed and the residuals stay within range, these are positive signals that imply that assumptions are met. If discernible trends can be detected, it would indicate that other models would be more adequate (e.g. higher degree polynomial functions).



(a) Residual Plot.



(b) Linear Regression Model.

Fig. 4.21. Residual Plot and Linear Regression Model.

After it was found that the data complies with the assumptions, consequently, the linear regression model was applied. The results from the regression model show that the R-square value is close to 70%. This numerical value characterizes the extent that one variable depends on the other. In the majority of the cases, the dependent variable cannot be fully justified by the independent variables (i.e. R-square of 100%). However, broadly speaking, an R-square value of 70% or above is sufficient. The analysis also provided a P-value, which was statistically significant with a value close to zero. Or in other words, a predictor with a low P-value is likely to be a meaningful addition to the model, because changes in the predictor's value are related to changes in the response variable [67]. Besides the aforementioned values, the regression model also provided an equation to describe the relationship between the dependent and the independent variable. The computed coefficient was approximately 2.4 ($y=2.43x$). In other words, it shows that the dependent variable increases by 2.4 as the independent variable increases with incremental steps of one. Hence, as the pavement age increases, the number of pavement failures increases along. This would imply that when maintenance is deferred, the pavement will continue to degrade, and each year, the number of failures will roughly increase by 6-10%. Despite that the obtained data shows a linear relationship between asphalt age and the number of pavement failures, this type of relationship still seems counter-intuitive. The primary reason stems from the maintenance strategy, which was depicted in Fig. 2.7. The strategy is based on a "wear-out strategy", which implies that in the period prior to large maintenance, less additional maintenance is conducted. The notion is to save expenditures, but simultaneously it would come at the expense of an increase in pavement failures. However, as the data shows a linear relationship, there is no sign of this behavior.

4.7.2 Multivariate Pavement Failure Analysis

With the Cox PH model, as described in Section 2.1.7, the pavement failures will now be analyzed with other predictors. Eventually, the pavement failures were all enumerated along with the circumstances under which it took place. Take notice, that multiple pavement failures may occur within an identified pavement grid. Furthermore, there are grids where no pavement failures have occurred in the recent years. In total, this concerns 154 pavement grids where no pavement failures have been recorded. This data cannot be neglected, as it shows that under certain circumstances the grids will have a longer survival chance. Fortunately, the Cox PH model is permitting censored or incomplete data [68]. In essence, one may discern between two types of censored data, left and right censored. For example, when a pavement grid has not reached its termination state, it is called right censored. For this particular case, right censored data are pavement grids where no pavement failures have occurred within 15 years. On the other hand, left censored data are pavement grids where the pavement age is unknown [40]. The underlying reason why this partial information may be used is that it has no effect on the distribution of survival time.

Upon implementing the Cox PH model, it was found that a minor data modification was required to attain a valid model. The deficiency was caused by the traffic intensity, which should be regarded as the natural logarithm. Recall that if x is the traffic intensity, the natural logarithm of x is ln(x) and since the natural logarithm is the inverse of the exponential function x is also equal to $e^{ln(x)}$. After conducting the test in SPSS, the first provided output is the Omnibus Tests of Model Coefficients (see Appendix F for a full overview of all the SPSS outputs). In this test the chi-square test is used to check whether the new model, including the explanatory variables, is an improvement over the baseline model [69]. In this case, the P-value < .000, hence the new model is significantly better than the baseline model. In addition, a step curve survival function was created as output (see Fig. 4.22a). Take notice that this curve only concerns an average pavement grid with average parameters for each of the variables, these values are depicted in Table 4.5. Herein, junctions are cat (1), runway exits (2), runways (3), straight taxiway sections (4) and the bays are the baseline category.

Table 4.5. Covariate Means.

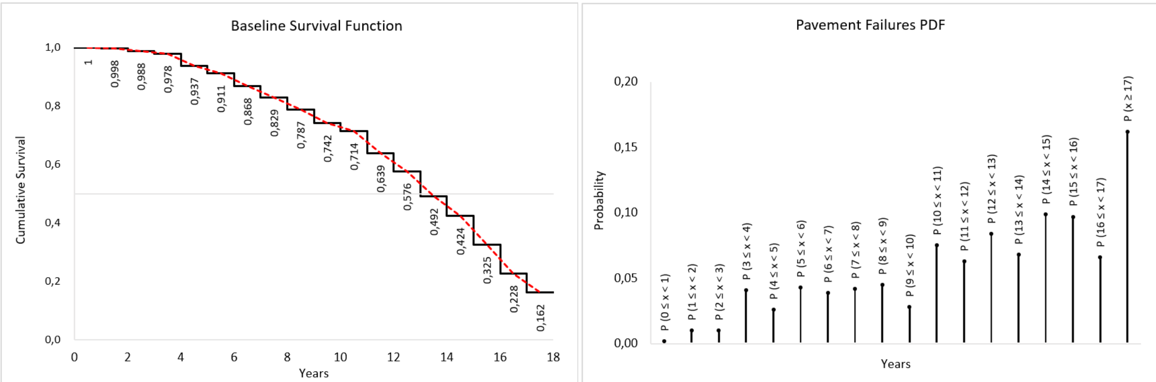
Variable Name	Mean	Coefficient (β)	Sig. P-value	95% CI Low/Up Exp(β)
Pavement Category 1	0.34	0.039	0.004	0.646/1.672
Pavement Category 2	0.07	-0.264	0.078	0.476/1.238
Pavement Category 3	0.16	-0.132	0.051	0.621/1.236
Pavement Category 4	0.22	-0.711	0.001	0.322/0.750
Surface Deflection	258.9	0.000	0.077	1.000/1.001
Aircraft Speed	8.56	-0.039	0.019	0.931/0.994
Stationary Traffic	2.22	0.158	0.006	1.047/1.310
Log Traffic Intensity	10.63	0.238	0.000	1.111/1.449

The corresponding survival curve depicts the probability that a pavement will be free of pavement failures beyond a specified time and is automatically created by using Eq. (2.5). Or in plain language, it shows what the chance is that an arbitrary pavement grid will be pavement failure free after a given period (i.e. survive it). Hence, the chance that a pavement grid is free of pavement failures at its 10th year is 74%. As the pavement grid becomes older, the probability of pavement failure manifestation increases and the survival probability decreases. Alternatively, since the chance on survival or being pavement failure free, at the 10th year is 74%, it can also be said that 26% of the pavement grids that are subject to the same circumstances, would have failed by that time. All of this information is based on the input of the pavement failure data, in which the age of the asphalt layer at time of failure emergence was incorporated as input for the model.

Recall that Eq. (2.5) consists of the baseline hazard function and the exponential function. The latter merely involves the influential factors, which are time-independent [41]. This implies that the baseline hazard function is the only part in the equation that causes the survival function to decrease over time. However, since $h_0(t)$ is approximated at each time point without explicit expression, the corresponding values are not provided as output, but directly incorporated in the survival curve [40]. This also justifies why the Cox PH model is often referred to as a semiparametric model. Besides the survival curve, also the median survival time is shown for the average pavement. In this situation, the median survival time is over 13 years.

The survival curve may also be transformed into a probability density function by computing the differences in survival probabilities for each year. By doing so Fig. 4.22b was created, take notice that since it is a probability density function, the sum of these probabilities equals one. This figure shows the probability that a pavement failure will occur within a given time interval. It is noticeable that the probability of pavement failures is progressively increasing. In the light of deferred maintenance, this figure depicts that the older the pavement, the higher the chance on a pavement failure.

Thus, deliberate procrastination of pavement goes hand in hand with higher chances of pavement failures. At first, the chance on a pavement failure is very low. Deferring maintenance at pavement sections that are younger than 10 years, has little consequences. However, the probability density function also shows that the probability of pavement failures for a 12-year-old pavement section is about 50% higher than the probability of pavement failures on an 8-year-old pavement section (see Fig. 4.22b). This proves the validity of the hypothesis that the chance of pavement failures increases a pavement section becomes older. Thus initially, the consequences of deferring pavement maintenance is limited, but increases over time as the pavement section approaches its 10th or 15th year of existence.



(a) Survival Function for an Average Pavement. **(b)** Probability Density Function.

Fig. 4.22. Survival Curve and Probability Density Function.

Lastly, it must be stressed that it is difficult to accurately infer what is occurring when the asphalt layer becomes older than 17 years. The source of this issue is that merely a select number of asphalt layers make it to their 17th year, as the maintenance interval is around 15 years. Ideally, perpetual asphalt would render the analysis easier, because this really shows how the asphalt behaves after a prolonged period of use.

4.7.3 Evaluation of Influential Factors

The efficacy of the Cox PH model lies in the fact that it can also considers influential factors. This provides the option to evaluate how various factors contribute to the survival curve, but more importantly, it can be determined how the survival curve alters due to a parameter change. This notion is analogues to a sensitivity analysis. To compute a survival curve that is tailored to specific pavement circumstances, let the baseline survival function in Fig. 4.22a be $S(t, x_m)$. This baseline survival function for an average pavement grid is then used to formulate a function describing the survival probabilities with parameters other than the average. This function is expressed as Eq. (4.1) and entails the mean parameters and the coefficient. In addition, a new variable x′ is introduced, which is the value of the altered parameter. For example, if x_1 concerns the traffic intensity and the mean is 41,300, the natural logarithm is 10.63. To evaluate the effects of a 10% increase in traffic intensity, x'_1 should be ln(45,400)= 10.725 (ln(x)=$log_e(x)$). In this particular case, $\Delta x_1 > 0$ and $\beta_1 > 0$, implying a higher chance on a pavement failure and hence a lower survival time. Take notice that other x'_n values should be equal to the mean to nullify the effects of the other factors.

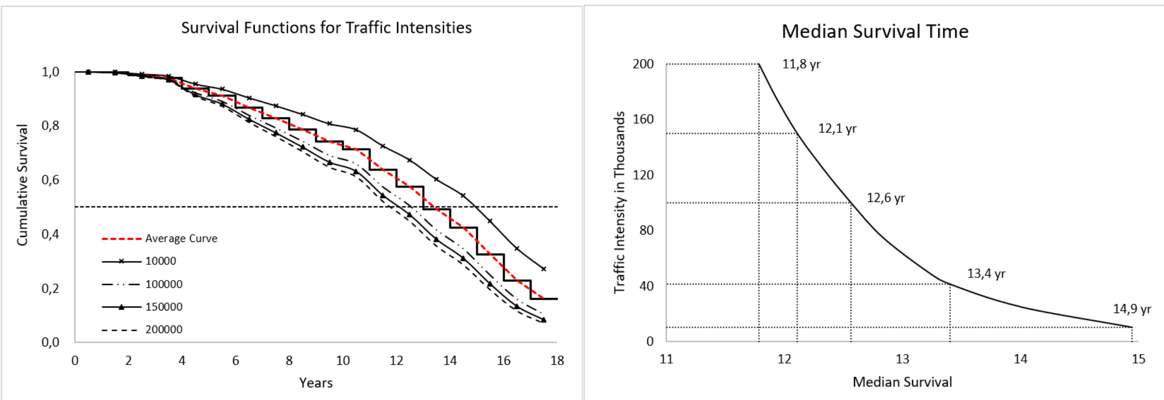
$$S(t, x) = S(t, x_m)^{exp[\beta_1 \cdot (x'_1 - x_1) + \ldots + \beta_n \cdot (x'_n - x_n)]} \tag{4.1}$$

By substituting the parameters in Eq. (4.1) with the numerical values of Table 4.5, Eq. (4.2) is obtained. By using this formula, the effect of each parameter can be evaluated. This can be done for a single parameter, while the other parameters are negated, or the combined effect of two or more parameters. Recall that this formula inherits the baseline survival function, thus filling the mean for every x'_n would yield the same curve as Fig. 4.22a.

$$log[S(t,x)] = log[S(t,x_m)] - 0.04 \cdot (x_1' - 8.56) + 0.16 \cdot (x_2' - 2.22) + 0.24 \cdot (x_3' - 10.63) \\ + 0.04 \cdot (x_4' - 0.34) - 0.26 \cdot (x_5' - 0.07) - 0.13 \cdot (x_6' - 0.16) - 0.71 \cdot (x_7' - 0.22) \quad (4.2)$$

To exemplify how this function works and to evaluate the alteration in the survival curve, the aforementioned example with the traffic intensity will be used. So in essence, the average traffic intensity is 41,300 movements annually. To evaluate how an increase in traffic intensity affects the survival curve, five traffic intensities will be used as x_3' in Eq. (4.2). Recall that the natural logarithm of these values must be taken: S=$\{10,000, 100,000, 150,000, 200,000\}$. Consequently, the corresponding functions were projected in Fig. 4.23a as a function of time. It is noticeable that there are no pronounced differences in the various survival curves, belonging to different traffic intensity parameters. This was anticipated as an increase of traffic intensity from 41,300 to 100,000 is only incremental when taking the natural logarithm ($\Delta x_3 \approx 0.88$) and the traffic intensity β coefficient in Table 4.5 is relatively small. Furthermore, it is shown that an increase in traffic intensity will increase the risk of a pavement failure emerging, which is also explained by the fact that $\beta > 0$. It is actually the 50

To quantify how the traffic intensity affects the survival curve, the median survival time is often used. The median survival time is the moment in time, at which the probability of being failed is equal to 50%. This can be found with a horizontal line of 0.5, which intersects the survival curve. This horizontal line is also exhibited in Fig. 4.23a. However, since it concerns marginal differences in median life, it is difficult to correctly interpret the different median life's. Therefore Fig. 4.23b was created, which is a curve showing the median survival time. This was attained by creating a number of survival functions for different traffic intensities, subsequently for each survival curve the median survival time was determined. Thereafter the median life's were projected as a function of traffic intensity. In addition, the median graph highlighted the corresponding median survival time of the projected survival curves from Fig. 4.23a. One can better perceive the differences in the median survival time now.



(a) Survival Function for Different Traffic Intensities. **(b)** Median Survival Time vs Traffic Intensity.

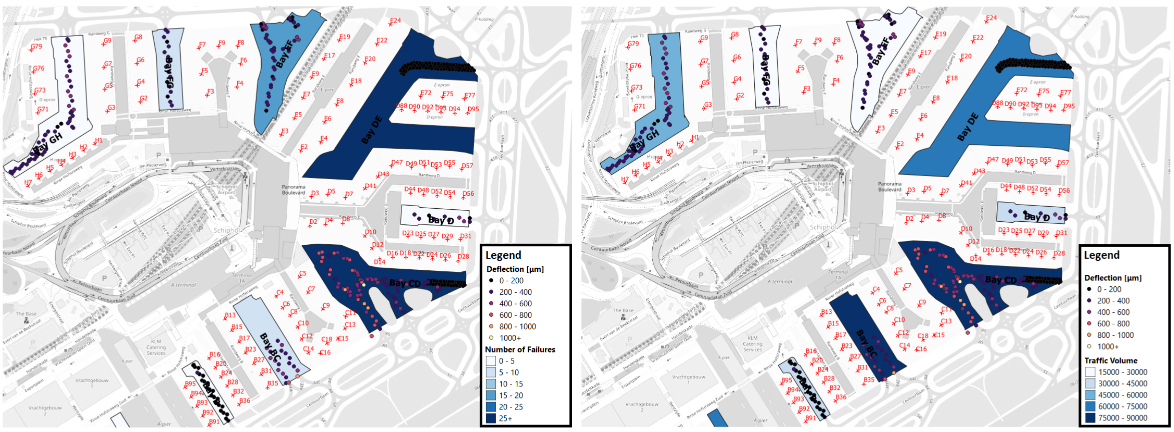
Fig. 4.23. Survival Curves and Median Survival for Different Traffic Intensities.

Effects of Traffic Intensity

At first glance, the effect of traffic intensity seems trivial, but a closer look at Fig. 4.23b shows that the effect cannot be neglected. It shows that a pavement grid that is subject to a large number of traffic has on average a lower median life. At contrary, the median life may increase by three years, if only a select number of traffic is using the pavement. It is also noticeable that the median survival time has a vertical asymptote, this is an inherent characteristic of an exponential function. Hence, the decrease in the median life will stagnate at a certain point, regardless of the traffic intensity increase.

Effects of the Surface Deflection

The effects of a higher or lower surface deflection seems to be absent, since the corresponding coefficient is zero. This was already anticipated, before the model was applied. For example, the average and median surface deflection for the runways shown in Fig. 4.9, are substantially higher compared to the other averages and medians. Meanwhile there were only a minimal number of pavement failures at runways. Despite the contradiction, various studies provided conclusive evidence that underpins why the deflection on the runways are among the highest [70]. According to Dai et al. [71], the imparted dynamic load during landing is more than twice of the total aircraft weight, as the vertical velocity of an aircraft during landing is about 2.6 m/s. Hence, the TDZ of a runway foundation is the area with the highest stresses due to landing forces and therefore shows the maximum deflection [70]. A closer look at the surface deflection measurements reveals that the surface deflection measurements for certain sections are considerably higher. However, this does not apply for the TDZ areas. To be more specific, this merely holds true for some sections of the Aalsmeerbaan and Oostbaan. Determining the averages for individual runways, disclosed that indeed the surface deflection results for these runways are significantly higher (respectively 419 and 583 μm). This is possibly due to the fact that these runways are much older than the other runways, hence they are closer to the end of its lifespan. When discarding the measurements for the Aalsmeerbaan and Oostbaan, the average surface deflection for runways is only 280 μm. Albeit still on the high side, it is certainly closer to the average surface deflection of the other types.



(a) Deflections Overlaid on Failures. **(b)** Deflections Overlaid on Traffic Volume [65].

Fig. 4.24. Surface Deflection Results for the Bays.

Not only the surface deflection measurements of the runways were exceptionally high, also the average for the bays was considered on the high side. In Fig. 4.24, the measured surface deflection at the bays can be observed. These deflection measurements are overlaid on the number of pavement failures and the traffic volume that correspond with the bays. Fig. 4.24a shows that the largest surface deflections were recorded in the CD bay. Moreover, the highest number of pavement failures were also found in this bay. However, also in BC and GH bay, moderate to high deflections were detected, unlike CD bay, the number of pavement failures in these bays remained proportional. The lack of evidence, that points out that pavement sections with high responses (i.e. impaired foundation) lead to more pavement failures, is conceivably justified by the fact that the majority of the observed pavement failures are functional failures (e.g. block cracking, raveling and weathering) [72]. Unlike structural failures, these functional failures are developed at the top layer of the pavement, hence they are not the result of a compromised foundation. Structural failures on the other hand, such as rutting and alligator cracking, are initially formed in the bottom and will propagate to the surface [58]. These structural distresses can be the result of an impaired foundation, however, these are seldom detected on Schiphol [72]. So in essence, the data gives no conclusive evidence that supports the notion that pavement sections with high surface deflections lead to more pavement failures. This notion is shared by other studies, that have also endeavored to find a relationship between pavement distresses and surface deflections. For instance, pavement related data studied by Baladi et al. [58] showed that evidence proving that distresses are the result of a compromised foundation is absent. Furthermore, Walker and Yoder [73] also studied pavement data, similarly they did not find a significant correlation between surface deflection and pavement distresses. Hence, the deflection data cannot justify why the junctions and bays are more prone to pavement failures.

Nonetheless, the pavement deflection data can still be used to identify impending structural distresses, so corrective actions can be taken prior to the manifestation of surface defects [58]. For instance, Baladi et al. [58] argued that alligator cracks stem from the bottom of the asphalt layer and propagate towards the surface. Ultimately, the pavement starts to impair as the crack is further developing. However, before the alligator cracking is appearing on the surface, it can be detected by the deflection measurements, because the response of the pavement structure load would increase [58]. This is also valid for pavement rutting, as Leiva et al. [74] showed large differences in the magnitude of the deflections measured where the pavement is rutting compared to areas with no evidence of rutting.

Lastly, Fig. 4.24b showed that a clearer relationship can be found between the measured deflection values and the traffic intensity. For instance, the highest deflection measurements were recorded in the BC, CD and GH bays. Concurrently, these bays also handle most of the traffic. Other studies have also addressed that the surface deflection increases over time due to internal and external effects, because the surface deflection is a materials' response to traffic loading. Hence it is dependent both on materials properties and loading conditions [75].

Effects of the Pavement Category

The pavement section categories were coded as dummy variables since it is a nominal variable without an intrinsic order. Unlike scale variables, a nominal variable works with a baseline. The baseline is in this particular case the bay areas, the other pavement categories (i.e. junctions, exit, runways and straight sections) are then compared to this baseline. In Fig. 4.25 the survival curves for the different pavement categories are shown. In essence, it shows that the bays (baseline) and junctions are alike in terms of survival curve and median survival life. On the other hand, runways and the runway exits seem less vulnerable and have a higher median survival life. Then finally, the straight pavement sections are the least susceptible to pavement failures.

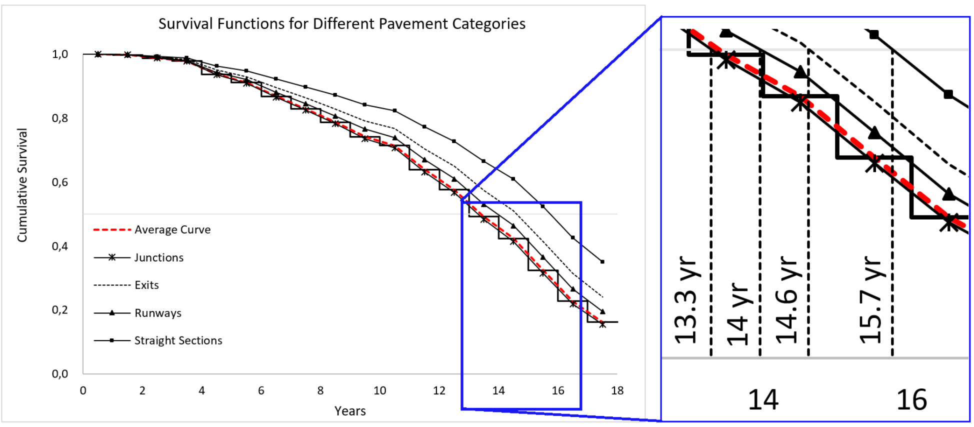


Fig. 4.25. Survival Function for Different Pavement Categories.

The suspicions that some sections are more prone to pavement failures is confirmed by the pavement analysis. However, it is extremely important to consider that the survival curves do not show how often a pavement failure has emerged in particular pavement categories, although the frequency has been considered in the input for the Cox PH model. What it does depict, is that certain pavement categories are less likely to be pavement failure free after a particular period. Therefore, it is interesting to examine what the extent of differences is in the number of pavement failures at different pavement categories. For this purpose data pertaining to the number of pavement failures per pavement category was assembled and consequently depicted in Table 4.6.

Through Table 4.6, it becomes evident that the number of pavement failures at certain areas are significantly higher. However, values in the third column do not reckon with the total size of the area of each section type, this could yield a biased view. Therefore, the number of pavement failures, in the third column, were normalized by considering the area. This would provide a more equivalent comparison. The normalized values are depicted in the last column of Table 4.6, which illustrates the theoretical number of failures when each type of section would be equal to one km^2. In principal, when the spatial scale is converted to one km^2, the number of pavement failures on runway exits would increase pronouncedly in comparison to other sections. To a lesser extent, this is also valid for bays. Generally speaking, the order shown in the last column still coincides with the order shown in the third column, with the exception for runway exits.

Table 4.6. Pavement Failures when considering the Spatial Scale.

Type of Section	Total area km^2	Number of Failures	Failures per km^2
Bays	0.54	112	207
Straight Sections	0.92	59	64
Junctions	0.99	131	132
Runways	1.45	65	45
Exits	0.16	24	150

With the information derived from Table 4.6, it is possible to determine the probability density function for each pavement category. However, as it concerns categories, it would be a discrete distribution for nominal categories (no intrinsic orders). The computed probabilities are illustrated below for S= $\{Bays, Straight\ sections, Junctions, Runways, Exits\}$. For each category, the corresponding probability is computed by dividing the (theoretical) number of failures per category by the total number of failures. These (theoretical) probabilities show the probability of a pavement failure occurring at a specific type of section, when considering the spatial size of each section type.

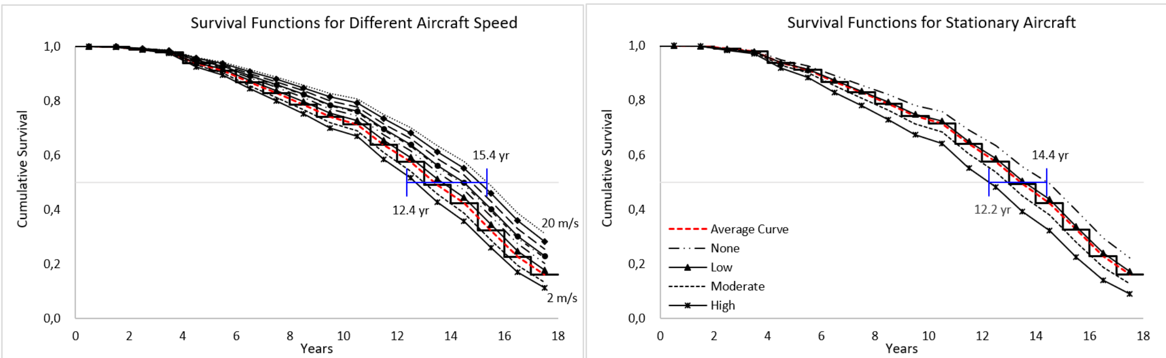
$$P(x) = \begin{cases} 0.35 = \frac{7}{20} & \text{if } x \in Bays \\ 0.11 \approx \frac{1}{9} & \text{if } x \in Straight\ sections \\ 0.22 \approx \frac{2}{9} & \text{if } x \in Junctions \\ 0.07 \approx \frac{1}{14} & \text{if } x \in Runways \\ 0.25 = \frac{1}{4} & \text{if } x \in Exits \\ 0 & otherwise \end{cases}$$

The probabilities show that the bay areas are pronouncedly sticking out. According to the details, there are 40% more pavement failures in the bays than at junctions or at runway exits. Compared to the straight sections, pavement failures are three times more likely to occur in the bays, moreover, for runways it is even five times as likely. The latter seems to be least susceptible to pavement failures. These observations are as anticipated. In the bay areas, airplanes turn, brake, are pushed back and they operate at a low speed, furthermore, they are more likely to stand still in these areas, awaiting for instructions. As aircraft slow down during taxiing, the duration which the pavement is incurring pressure, increases and ultimately it will quicker result in a certain terminal condition of deterioration. Conversely, as aircraft rapidly cross the pavement section, the contact moment between the aircraft undercarriage and tarmac is limited and less damage is exerted on the latter. Hence, mainly the extent of each loading seems to be the real culprit. This is also the reason why the pavement of aprons, where aircraft stand still for long uninterrupted periods, are erected with concrete due to its robustness [76]. Ultimately, as asphalt has different properties, still standing aircraft intensify the number of pavement failures. This notion is underpinned by the study of Sultan [25]. In this study it is addressed that static wheel loads and the loads during the braking maneuver are more detrimental than the imposed loads during a moderate speed. Pertaining to the latter, one could argue that if this holds true, the number of pavement failures in the touchdown zone must be significantly higher than in other areas. Possibly, due to the fact that the touchdown zone is replaced in a shorter time interval than other sections, this was not observed. For other sections on the runway, the contact moment between pavement and the undercarriage is limited to merely fractions of a second, due to the velocity of the aircraft. Moreover, due to its velocity on the runway, the aircraft will not exert full pressure on the tarmac. This is because the lift force $\propto v^2$, which indicates that the magnitude of the lift force is still substantial [77]. In other words, when the aircraft rolls at a high speed, the loading phenomenon is transient and less severe due to lift forces created by the wings of the aircraft [70]. This notion is confirmed by Hveem [45], which argues that it is widely known that taxiways are usually the first to show signs of distress. Runways on the other hand, do not ordinarily present a serious problem, since the load effects on runways are minor due to the fact that a considerable percentage of the load is still airborne until the plane has reached the taxiway [45]. Finally, landing aircraft are lighter than departing traffic, which further diminishes the potential load. A combination of these factors may be the reason why only a small number of pavement failures have been observed on runways.

Junctions on the other hand, are more prone to pavement failures. A possible explanation is that an abundance of traffic comes together at junctions and that aircraft can make turns here. This may also justify why the recorded number of pavement failures at runway exits are on the high side, as many runway exits have a curvature geometry.

Effects of Aircraft Speed and Stationary Traffic

Then related to the aircraft speed, it was found that it has a marginal effect. However, as a wide range of aircraft speed options are available, the median survival life may change to a large extent. In Fig. 4.26a the survival curves for an aircraft speed varying from 2 m/s to 20 m/s are shown (steps of 2 m/s). It shows for a ΔV of 18 m/s, that the median life increases by three years. As mentioned before, when an aircraft rapidly crosses a pavement section, the contact moment between the aircraft undercarriage and tarmac is limited and less damage is exerted on the latter. Hence, a lower aircraft speed is more harmful.



(a) Survival Function for Aircraft Speed. **(b)** Survival Function for Stationary Aircraft.

Fig. 4.26. Survival Function for Aircraft Speed and Stationary Aircraft.

Then pertaining to stationary traffic that impose static loads, Fig. 4.26b shows that the extent to which the pavement grids are subject to stationary aircraft were coded as an ordinal variable. In essence, pavement grids that are subject to a large amount of stationary aircraft have a lower median survival life (12.2 years). Conversely, pavement grids where no stationary aircraft were recorded prove to be less susceptible to pavement failures and therefore have a median survival life of 14.4 years. This phenomena was expected, as Sultan [25] addressed that static wheel loads and the braking maneuver are more detrimental than the imposed loads during a moderate speed. Furthermore, after being motionless, the aircraft has to accelerate to regain speed. This can also be a factor that should be considered.

After assessing the individual effects of the influential factors on the shape of the survival curves, it was endeavored to conduct a sensitivity analysis to compare the importance of the different influential factors vis-à-vis. However, since there is a mix of continuous and categorical variables, the analysis was impeded because there is no unified scale for the variables, for example categorical variables cannot be increased by a given percentage (e.g. 10%, 20%). Nonetheless, the exhibited survival curves for different circumstances in this section, has provided a proper impression of the magnitude of effects of the different influential factors.

4.8 Chapter Conclusion

This vast chapter elaborated on many aspects, therefore this chapter will be concluded with a brief summary of the most pithy insights. In essence, the former sections of this chapter started broad by acquiring pertinent data relating to the pavement and airport operation. Thereafter, the entire Parcel one acreage was segregated into 300+ respective pavement grids. The obtained data was then embedded into the corresponding pavement grids. This allowed the differentiation of the pavement grids based on the attributes, for instance, the number of traffic that passes the pavement grid, along with the average taxi speed, the asphalt layer age and characteristics pertaining to the pavement foundation. This information was then used in the data analysis phase, wherein the Cox PH model was used to analyze under which circumstances pavement failures emerge.

The results of the data analysis provided promising insights. For example, based on the observed age of the asphalt layer at the moment the pavement failure emerged and other attributes, the analysis showed that an average pavement grid has 50% chance to remain pavement failure free when it turns 13 years. As time passes, the chance reduces and ultimately $S(\infty) = 0$. This shows that the older the pavement, the higher the chance of pavement failures, which is an adverse effect of deferring maintenance. Most notably, the chance of pavement failures increases disproportionately after the asphalt layer has becomes older than 12 years. Moreover, the analysis showed that different parameters for the assessed factors will alter the shape of the survival curve. Through the generated regression equation (Eq. (4.2)), which can be tailored to the specific circumstances, the magnitude of effect of the different influential factors was assessed. It showed that the surface deflection has no or only a neglectable effect on the manifestation of pavement failures. Furthermore, the aircraft speed shows to have a linear effect. Or in other words, a higher aircraft speed mitigates the chance of pavement failures. Traffic intensity and stationary traffic on the other hand have reversed effects, the lower the traffic intensity and stationary traffic, the greater the longevity of the pavement. Furthermore, discerning between different pavement categories proved to be fruitful, as the data analysis showed that pavement failures appear to emerge quicker at junctions and the bay areas.

Chapter 5

Operational Impact of Pavement Failures

5.1 Introduction to Schiphol's Taxiway and Runway Systems

Schiphol is a hub in a global network of connections. With six runways, Schiphol handles a large amount of incoming and outgoing traffic, with peaks of up to 100 flights per hour [64]. The infrastructure and assets at Schiphol are the core nodes in the operation of the airport and they can be seen as a "system", with a cluster of objects or subsystems that interact together and form a unified whole. The subsystems in this overarching system are the runways, taxiways, terminals, aprons and bays. Each of these subsystems have their individual responsibilities in this system and cannot independently fulfill the role of handling landing and departing traffic. This chapter will evaluate the operational impact of a closure of one of these subsystems. However firstly, it is of essence to firstly introduce the taxiway and runway systems.

5.1.1 Taxiway System Schiphol

Taxiways are defined paths on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another, according to the definitions by ICAO [6]. For Schiphol Airport, the taxiways connect the bays and platforms with the surrounding runways. The heart of Schiphol's taxiway system primarily consists of taxiways Alpha, Bravo and Quebec. The standard taxiing protocols describe that the parallel taxiways, Alpha and Bravo, have predefined taxi routes. Hence, the former is mainly used for clockwise traffic and the latter for anticlockwise traffic, together enabling two-way traffic. Adherence to these protocols is obligatory, unless otherwise instructed by the air traffic control [62]. Taxiway Quebec, on the other hand, is a two-way taxiway. However, it is soon to be replaced by a parallel taxiway, thereby enhancing traffic flows and mitigating the overall taxiing time.

5.1.2 Runway System Schiphol

Runways are areas on a land aerodrome prepared for the landing and take-off of aircraft according to the definitions by ICAO [6]. The six runways of Schiphol airport are connected via taxiways to the terminals. The landing and departing traffic are, again, administered according to strict procedures. These procedures entail a runway preference scheme, which is exhibited in Fig. 5.1. This scheme is enacted by considering the climatic conditions, the operational demand and the residents in the vicinity, that incur noise disturbance [63]. It shows which runways are most preferred for landing and departing operations, if the circumstances inhibit the use of the most preferred runways, the next in the queue will be exploited.

5.2 Operational Impact due to Traffic Detour

To investigate the operational impact, the most prevalent routes from the bays to the runways will be determined. By identifying the possible taxi routes from the bays to the runways, the corresponding distances of the routes can be determined. Thereafter, for each route the theoretical taxi duration can be computed. With this information, it could be determined what the extent of detour is when a

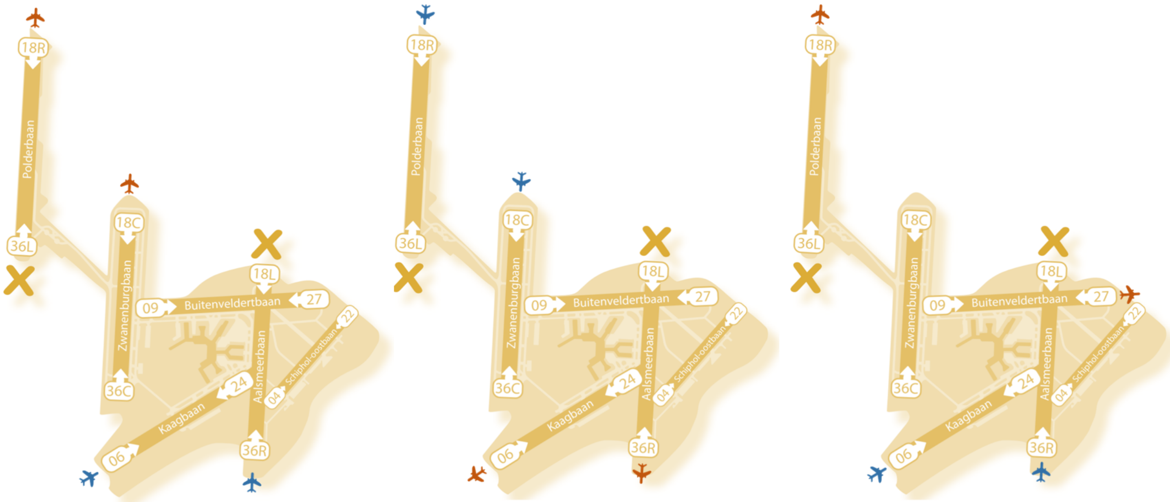


Fig. 5.1. Runway Use Preference Prioritized from Left to Right [63].

certain section is shut off. Then, the additional taxi time (which is the impeded taxi time - unimpeded taxi time), can be translated into costs, as various studies have quantified the costs of delay. To attain all of this, intermediate steps have to be taken, which will eventually come together. Firstly, the average taxi speed and the different taxi routes need to be determined. Thereafter, the traffic delay costs will be determined. Ultimately, with this information, the operational costs for traffic detour can be computed by envisioning the occurrence of pavement failures at some taxiway sections.

5.2.1 Taxiway Network of Schiphol

A road network is a system of roads that are connected via intersections. These networks can be simulated in a geographical environment according to graph theory, by creating a graph with a set of nodes and links. This theory has found significant application to the analysis of transport networks, where there is an intuitive and obvious relationship between the links and nodes in the transport network [78]. Unlike for regular roads, there is unfortunately no readily available road network for the taxiway system of Schiphol. Hence, a graph tailored to the taxiway system of Schiphol was erected with information from Jeppesen navigational charts. The network of nodes and links that was drawn over a map of Schiphol is illustrated in Fig. 5.2.

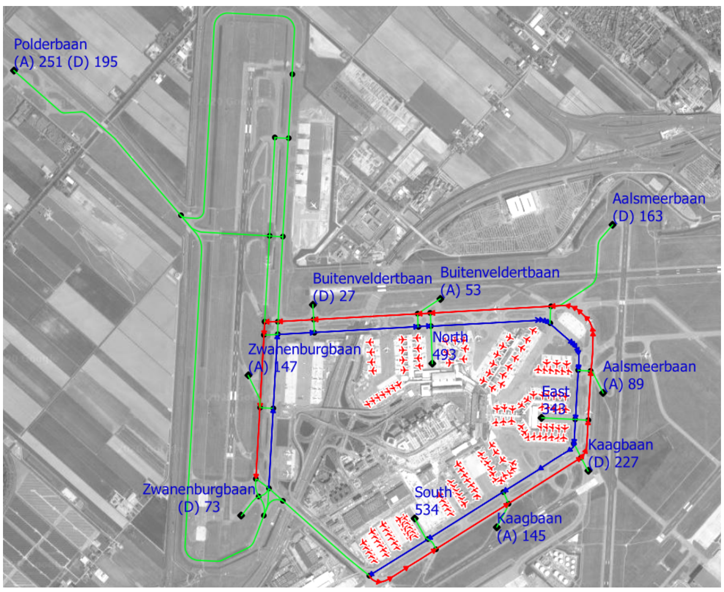


Fig. 5.2. Taxiway Network of Schiphol with Average Taxi Time.

In essence, the links in this graph represent the taxiways of Schiphol, whereas the nodes represent the junctions where two or more roads meet. The graph discerns between three types of links, namely bidirectional, clockwise directional and anticlockwise directional taxiways. Furthermore, various destination/origin points have been defined at runway entrances and the bays. However, since each runway has various exits and entrances and there are numerous gates, the graph complexity will increase rapidly. To mitigate complexity, only vital runway entrances and exits have been defined as a destination/origin nodes. These were chosen based on the origin-destination matrix depicted in Appendix E, which showed the most frequently used runway entrances and exits. Pertaining to the Polderbaan, as this runway is only connected to one taxiway, there is only one defined destination/origin node for this runway.

Then for the airport gates, a different approach was taken as Schiphol has over 100 gates in total. By categorizing the gates based on their geographical location, three classes were identified, namely North, East and South gates. The gates from bays EF, FG and GH, bays CD, D, DE and bays A, B, BC belong respectively to the North, East and South gates. Thereafter, a representative destination/origin node was computed for each region, by using Eq. (5.1). This equation seeks the centroid of a set of longitude and latitude coordinates. However, it must be emphasized that the average longitude is more intricate to compute and was determined with a different formula. But due to the irrelevance of explaining the trigonometry of determining a centroid, the formula for the average longitude was omitted. Finally, after the essential components of the network were specified, the taxiway network was used in the succeeding section.

$$(x, y) = \frac{1}{n} \sum_{i=1}^{n} (x_i, y_i) \tag{5.1}$$

5.2.2 Route Travel Time Estimation

The taxiway network allows the identification of possible routes from the gates to a given runway. However, to actually determine what the operational impact is when a pavement failure emerges on a given taxiway, the taxi time must be determined for the primary route and its alternatives. This introduces the shortest or fastest path problem, which is a common problem in the realm of transportation and network design [79]. For this reason, the taxiway network was erected, as it offers a unique solution to this very common spatial problem. In this network, each link contains the distance attribute, so by following the links that reside between two selected points, the distance can be computed. However, this is extremely tedious and it merely shows the distance of an arbitrarily chosen path and does not find the shortest path and its corresponding distance. For this purpose, a shortest path algorithm can be used which is readily available in GIS (e.g. Dijkstra's shortest path algorithm). This algorithm aims at finding the shortest path to the goal node from a single source node in a vertex graph or network [80]. To exemplify how such a concept works, see Fig. 5.3. In essence, it commences with the node on the left side of the graph, which is denoted by a zero. The algorithm then seeks the shortest paths to the nodes in the direct vicinity. This is again done for the nodes in the direct vicinity of the starting node. In some cases, a shorter path can be found via an intermediate node, like for the node on the bottom left corner (i.e. 6+2 < 9). Take notice that the nodes show the shortest travel distance from the starting nodes. Through this iterative process, the shortest path from one point to another can be found, in this particular case the shortest path is denoted with arrows.

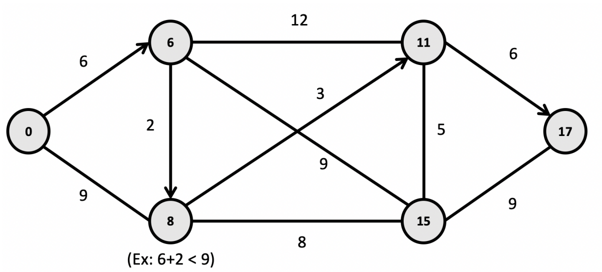


Fig. 5.3. Principles of the Shortest Path Concept.

An algorithm following the same principles was used to determine the shortest path between a given start and an end node in the taxiway network. However, instead of the shortest path, the fastest path was determined, which is done by adding an aircraft taxi speed attribute to each link with the information from Fig. 4.18a. The notion of a fastest path is analogous to the shortest path principle, but there is an intermediate step in which the distances are converted to travel times.

5.2.3 Traffic Detour in Minutes

Now the taxiing speed and time has been incorporated into the taxiway network of Schiphol, it must be determined how many minutes the total traffic is taxiing in the base scenario on an average day. The base scenario is assumed to be an average day without disturbances nor congestion. Furthermore, accumulated taxi time for all aircraft, for a given day, depends on the runway use and the number of movements for that day. However, these factors happen to depend on the wind direction and the type of day (e.g. high or low season, day of the week etc.). Hence, instead of randomizing these factors, an average daily departing or arrival movements of 1370 (500,000/365) is assumed, which are distributed from the bays to the runways and vice versa according to the details described in Section 4.5.

In principal, 39% of the traffic either stems from or goes to the gates in the south (bays A, B and BC). The fraction of the traffic for the gates in the east (bays CD, D and DE) is 36% and the remainder belongs to the northern gates, comprising of bay EF, FG and GH. This traffic either stems from or goes to the runways. According to Table 4.1 around 60% of the total traffic uses the Polderbaan or Kaagbaan. The remaining traffic uses the Aalsmeerbaan (18%), Zwanenburgbaan (16%) and Buitenveldertbaan (6%). This fraction can be further decomposed into departing and arriving traffic. The corresponding fractions have been multiplied by the average daily traffic and are depicted in Table 5.1. This table shows how the departing traffic is distributed among the different runways. Table 5.2 yields similar details, but this concerns the arriving traffic and shows how the traffic is distributed among the gates. Take notice that the total number of departing traffic should be equal to the total arriving traffic. This also holds true for the total departing and arriving traffic for each of the three gate categories. Take notice that the number of departing traffic and the number of arriving traffic for each of the runways is different, as some runways are used more intensely for take-offs than for landings or vice versa. This information pertaining to the traffic numbers are also shown in Fig. 5.2. For example, there are two nodes connected to the Zwanenburgbaan, one is a destination node and represents the departing traffic, whereas the other is an origin node that represents the arriving traffic. As mentioned before, 16% of the total traffic on Schiphol utilizes the Zwanenburgbaan. This implies that on average around 220 aircraft are handled daily by the Zwanenburgbaan alone, of which 147 are arriving and 73 are departing airplanes. Recall that the location of the origin and destination nodes are based on the most used exit and entrance at the given runway, which is retrieved from Appendix E.

Table 5.1. Distribution of Departing Traffic.

	Polderbaan	Kaagbaan	Aalsmeerbaan	Zwanenburgbaan	Buitenveldertbaan	$\sum x_i$
North Gates	70	82	59	26	10	247
East Gates	49	57	41	18	7	172
South Gates	76	88	63	28	10	266
$\sum y_i$	195	227	163	73	27	685

Table 5.2. Distribution of Arriving Traffic.

	Polderbaan	Kaagbaan	Aalsmeerbaan	Zwanenburgbaan	Buitenveldertbaan	$\sum x_i$
North Gates	90	52	32	53	20	247
East Gates	63	36	22	37	14	172
South Gates	98	57	35	56	20	266
$\sum y_i$	251	145	89	146	54	685

With the gathered information, the total taxi time for an average day can be computed. For this purpose, the taxiway network will be used in combination with the fastest path algorithm. It was done as follows, since Tables 5.1 and 5.2 show how the departing aircraft are distributed from the gates among the runways and vice versa for the arriving aircraft, the fastest path for each pair of origin and destination nodes was determined. In total there are 30 pairs, hence for each pair the fastest path was defined. Thereafter the taxi time of the corresponding path was determined. By multiplying the travel time of each path with the corresponding average traffic numbers, the total taxi time for each path can be determined. Ultimately, the total accrued taxi time for an average day can be computed by summing the total taxi time of all 30 paths.

For the baseline scenario, the average taxi time of the 15 departing paths is 6:32 min and 6:03 for arriving paths. This discrepancy is caused by the fact that the exits of runways are on average more adjacent to the gates than the runway entrances. Then pertaining to the individual runways, it was observed that the average taxi time from the gates to the Kaagbaan is the shortest with around 4:17 min. On the other side of the coin, with 10:15 min the taxi time to the Polderbaan is the longest.

Table 5.3. Total Taxi Time on an Average Day.

Taxi Time in	Seconds	Minutes	Hours	Per aircraft [min]
Taxi Time Departures	274,497	4,575	76	6:41
Taxi Time Arrivals	282,166	4,702	78	6:52

Now the taxi time of the various taxi paths are computed, the next step is to multiply these taxi times with the details from Tables 5.1 and 5.2. By matrix multiplications it was found that the accumulated taxi time for all departing traffic is 76.2 hours per day, for arriving traffic this is even 78.4 hours. These values are also exhibited in Table 5.3. In addition the average taxi time per aircraft is shown in the last column, which is computed by dividing the total taxi time with the number of aircraft (i.e. 685 departing and 685 arriving aircraft). Previously it was mentioned that the taxi time on the departing paths is longer than the arriving paths, however the tables have turned when considering the number of traffic that utilizes these paths. This is simply because the Polderbaan (farthest runway) is more used for arriving traffic and the Kaagbaan (closest runway) is predominantly used for departing traffic.

To come to the point, this table shows that the accrued taxi time on an average day is close to 9300 minutes, which is the baseline. To evaluate the extent of operational impact of a pavement failure, various links will be "closed-off" to mimic a pavement failure. This is simply done by modifying the distance of the link to a great number. The fastest path algorithm will automatically detect that the link, where a pavement failure is envisioned, is impractical due to its distance and will seek an alternative path. Ultimately, the links in Fig. 5.2 were modified one by one and the corresponding effect on the taxiing process was analyzed. In the majority of the cases there was only a moderate effect on the accumulated impeded taxi time. However, for a minority, there were large negative effects. Lastly, there were a few exceptional cases where the effect was neglectable, for example, taxiways which are seldom used or are secondary or tertiary options. Now the accumulated impeded taxi time for all traffic, after a given taxiway is shut off, is analyzed, the traffic delay must be quantified in terms of costs. This will be done in the subsequent section, which will proceed with the quantification of pavement failure effects.

5.2.4 Traffic Delay Costs

Operational Impact of Taxiway Closure

Upon analyzing the amount of minutes that airplanes have to detour when a pavement failure has occurred (impeded taxi time), the effects must be monetized. To do so, it was necessary to scrutinize pertinent documents that have elaborated on the operational costs of operating an aircraft. The referred to document, was published in 2016 by Eurocontrol [31] in collaboration with Cook and Tanner [81], which are affiliated with the University of Westminster. This document provides a set of input data, that are commonly used for airport related analyses and appraisals, such as financial analyses.

The section that is of particular interest, are the sections related to traffic delay. More specifically, the cost of delay during taxi in and taxi out, as other types of delay are different (e.g. enroute or at-gate delay). Furthermore, Cook and Tanner [81] discern between tactical and strategic delay. For this analysis only the former is of interest, as it concerns delay costs for unanticipated delays. The found delay costs per minute for an average European fleet mix is €52 for short delays of up to 30 minutes. These costs are merely averages and determined by considering the fuel costs, the operational maintenance costs and the service-hour costs for fleet and crew. Strategic passenger costs nor reactionary effects were considered herein, because the reckoned delay time is less than 30 minutes.

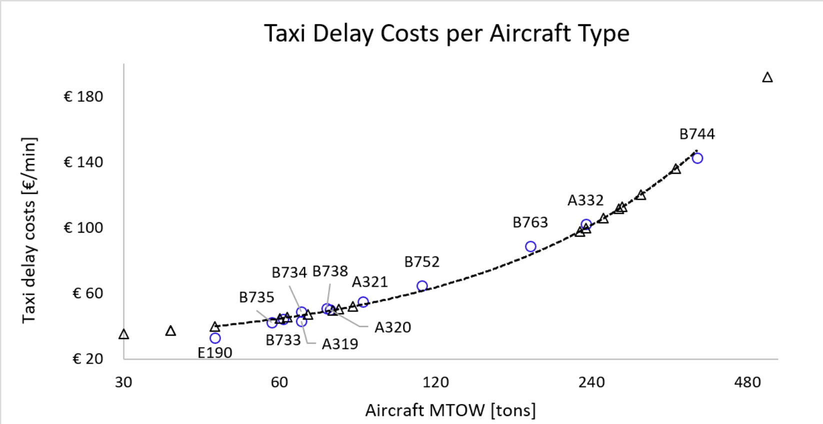


Fig. 5.4. Taxi Delay Costs per Aircraft Type.

In addition, taxi delay costs for ten specific aircraft types were found. These values were projected in a graph, as a function of the Maximum Take-Off Weight (MTOW). As shown in Fig. 5.4, the taxi delay costs of the ten aircraft types (depicted in blue) and the MTOWs appear to have a one on one relationship, with a near perfect positive correlation (R-value is 0.98). Using this correlation, the taxi delay costs can be determined for all other aircraft types, given the MTOW is known. Hence, this was done for the fleet mix of Schiphol, as shown in Fig. 5.4. Thereafter, the average taxi delay costs for Schiphol's fleet mix was determined, by considering the number of movements per aircraft type. However, as these numbers are from 2016, they had to be adjusted for inflation. The used inflation rates are from the Netherlands, retrieved from European Commission statistics. When adjusted for inflation, the average taxi delay costs for Schiphol's fleet mix boils down to 56 €/min for 2020.

By multiplying this taxi delay cost for Schiphol's fleet mix with the total taxi time from Table 5.3, the total costs of taxiing can be computed. For the baseline scenario this equates to €520,000 for an average day, without any detours. This is specifically for Schiphol's fleet mix and runway/taxiway layout and it furthermore considers inflation and an average number of movements. In a similar way, this can be done for the scenario's wherein certain taxiway sections were shut off. Thus for example, taxiway Zulu is out of operation and hence a fraction of the total traffic must take detours. This will increase the total taxi time, since some aircraft have a higher taxi time. This total taxi time is also called the impeded taxiing time. So after the impeded taxiing time is computed (in the previous section), it can be multiplied with the average taxi delay costs of 56 €/min. The result is a new total costs for a day of taxiing, which should be higher than the baseline scenario.

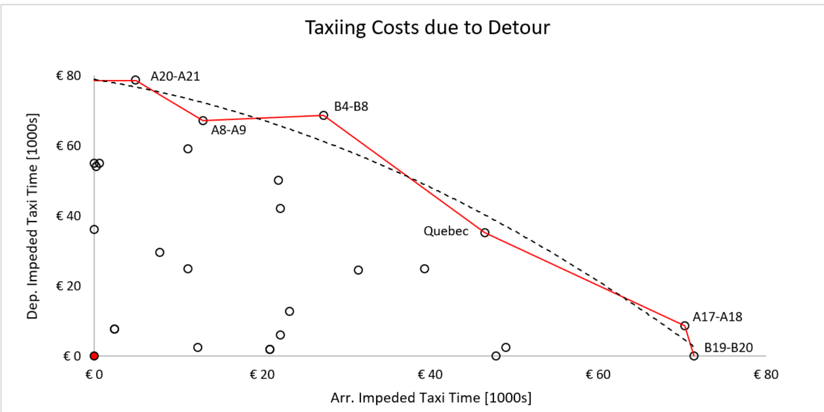


Fig. 5.5. Impeded Taxiing Costs.

Once this is done for all scenario's, wherein a pavement failure is envisioned for different taxiway sections, the daily impeded taxiing costs can be compared to the baseline scenario. The result is the excessive taxiing costs due to detour, which is also displayed in Fig. 5.5. The displayed costs were computed by deducting the baseline taxiing costs from the impeded taxiing costs, thus each point is referred to the baseline scenario, which is depicted as the (0,0) point in Fig. 5.5. Furthermore, take notice that these costs are separated into taxiing costs for arrival and departure airplanes, hence the sum of these components is the real daily additional taxiing costs.

In essence, with this figure one could infer the magnitude of impact for the operation when a pavement failure occurs at a given location. To further enrich the figure, a similar concept as the Pareto curve has been added. In opposition to the Pareto curve, which normally shows the non-dominated solutions, this curve shows where pavement failures would have the most operational consequences. Especially pavements failures at the Alpha or Bravo taxiway seem to have substantial impact. However, not all of the Alpha or Bravo sections are subject to the same extent of impact. Taxiway Bravo 22 until 26 for example, prove to be less affected by pavement failures. Furthermore, it should also be mentioned that taxiway Alpha and Bravo, despite officially being for unilateral directions, are in some occasions used interchangeably. Considering this, the operational impact of a pavement failure, emerging at either taxiway Alpha or Bravo, should only be a minor nuisance. However, this is not considered in the analysis, since the taxiway network in Fig. 5.2 adheres to the official directions.

When further scrutinizing Fig. 5.5, it becomes evident that taxiway Quebec is, operational wise, among the most critical taxiways (€81,500 additional costs). This is because all the traffic between the south gates and the Zwanenburgbaan and Polderbaan must take a detour and cannot utilize taxiway Quebec. This increases the impeded taxi time significantly. Conversely, one may pose the question, why is the operational impact of a pavement failure occurring at Whiskey 5 not among the most critical? The underlying reason is that only aircraft between the Polderbaan and the north gates are significantly affected, which is a relatively small group. Aircraft from other gates can take alternate paths that are only moderately longer. Therefore Whiskey 5 is not among the most critical taxiways.

Operational Impact of Runway Closure

The previous analysis has primarily emphasized on the taxiways alone, the operational impact of pavement failures on runways was not covered herein. This was done deliberately, because the closure of a runway is far more intricate to analyze. As no information related to this topic is available, an alternative approach was taken. Rather than stressing on the costs of a runway closure, the generated revenue streams per runway was analyzed.

As airports levy landing and take-off charges, the revenue stream for each runway can be determined based on traffic numbers. For example, Overeem [82] estimated that the five main runways of Schiphol Airport generated an accrued revenue stream of approximately €338 million in 2014. This is for a total of 437,000 movements. Albeit, the number of operations is a good indicator for the magnitude of revenues, this is not the only factor to consider. For an accurate estimate of the revenue streams, the fleet mix and the moment of the day (i.e. day or night) should also be considered, because different tariffs are charged for larger aircraft and night operations. When comparing the movements between 2014 and 2019, it becomes evident that the number of movements increased by 13.6%. However, the traffic in 2019 is still distributed among the runways in a similar fashion as in 2014, as depicted in Fig. 5.6.

Since the landings and take-offs are still similarly distributed, the data retrieved from 2014 can be generalized to 2019 with inflation and movement corrections. This yields a total revenue stream of €414 million in 2019 for the five main runways. Then for the individual runways, it seems that the Kaag- and Polderbaan are the most important runways in terms of revenue (respectively €149 million and €137 million). The Aalsmeer-, Zwanenburg- and Buitenveldertbaan generate a revenue stream of respectively €73 million, €32 million and €22 million. In essence, when solely considering these numbers, one may infer that a pavement failure has the highest operational impact at the Kaag- and Polderbaan. However, this would not be completely valid, since alternate runways are available to substitute the closed-off runway. Hence, these numbers still do not yield the answer to what the operational impact is of a runway closure. Therefore, the next section will devote attention to qualitatively address the operational impact of closing a runway.

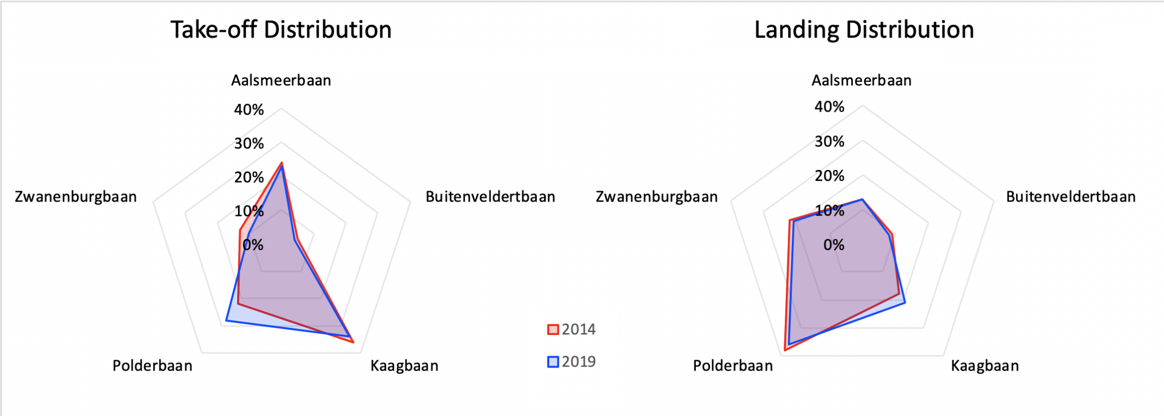


Fig. 5.6. Landing and Take-off Distribution among Runways 2014 vs 2019.

5.3 Case Study of Runway Closure Consequences

As Schiphol possesses multiple runways, one may argue that when a runway is closed-off due to a pavement failure, its function can be easily substituted by an alternative runway. To exemplify, at 09:00 am on the first of January 2020, the Polderbaan (18R) was used for landing. Conversely, the Aalsmeerbaan (18L) and Kaagbaan (24) were used for take-off. Meanwhile, at 10:00 am the runway use instructions were altered. Wherein the Polderbaan (18R) and Zwanenburgbaan (18C) were operative for landing traffic and the Buitenveldertbaan (09) was up and running for departing traffic. This reflects that the privilege, of having six runways, makes Schiphol versatile regarding runway use. Furthermore, one may even argue that there is overcapacity, since not all runways are occupied during peak moments, and hence the extent of operational impact of runway closure remains fairly restricted. However, on the long-term, certain rebound effects, that are absent at first, may emerge later on. In an endeavor to capture, and subsequently explain the complex dynamics of the operational impact of runway closure, a qualitative system dynamics model with the Polderbaan as case study, was erected. However, prior to elaborating on the model itself, the line of thought and the concept of system dynamics will be briefly introduced. Thereafter, the emphasis will be transferred to an introduction of the case study and lastly, the model will be explained extensively.

5.3.1 System Dynamics Introduction

System dynamics is a quantitative simulation modelling methodology for evaluating complex problems with dynamic behavior, feedback, and especially delayed feedback [83]. It was developed by Forrester in 1960s, who was affiliated with MIT [84] and is derived from systems theory, control theory and organizational theory [85]. It received abundant attention from the academic field of policy analysis and decision-making in transport [85]. Since its introduction, system dynamics has been applied in a myriad of fields. Among others, in the highway maintenance/construction, airlines and airport and strategic policy at urban, regional and national levels.

The fundamental tenet of system dynamics, and the starting point, are the casual loop diagrams. These diagrams capture the connections between entities by causal relationships and as the diagram develops, feedback loops become evident. These loops can be classified as, either, positive or negative. The former type of loops are reinforcing loops, this implies that they amplify what is happening in the system [85]. For example, an increase in one parameter leads to an increase in another, and without a balancing loop, this will result in an exponential growth until infinity. Balancing loops, on the other hand, have a counterbalancing effect, an increase in a certain parameter results in a decline in another. When systems contain balancing and reinforcing loops, a dynamic equilibrium will eventually be reached through their interplay [85].

System dynamics is based on linking differential equations, but is presented to the evaluator in terms of stocks and flows. Through stock-flow diagrams the model remains transparent and relatively easy to understand. These stock-flow diagrams are rendered after the CLD has been erected. Stocks are accumulations and are represented by rectangles suggesting a box to hold the content. Flows either flow into or out of stocks, these are represented by pipes with valves controlling the rate of flow into or out of a stock [83]. Often the bathtub metaphor is used to explain the concept and mathematics behind the simplest building block of a stock. The bathtub represents a stock that accumulates water over time due to the inflow, which is controlled by the tap. Simultaneously, the outflow is controlled by the pug. Behind the interface of the stock and flow diagram, hidden differential equations perform the computations to determine the alterations in the stock.

5.3.2 Polderbaan Case Study Introduction

Between the 14th and the 23rd of July 2018, the Polderbaan was inoperative, due to an unexpected emergency repair at taxiway Victor, that had to take place because of the presence of excessive amounts of water in the pavement [86]. Hereupon, the Polderbaan was closed-off for an entire week. This had various operational and technical consequences. To examine these effects, it is essential to introduce the five categories of consequences that are used by Schiphol to quantify impact. To quantify the impact of a failure, the following five pillars are used: safety, reputation, environment, operational availability and technical costs. Some of these impacts are less evident than others, due to their intangible nature (e.g. reputation impact) and hence more difficult to quantify or to monetize.

In Fig. 5.7, a system dynamics model is depicted, which demonstrates the different impacts of the Polderbaan closure. The model schematizes this event by a number of stocks, flows, variables and loops. Although system dynamics is inherently quantitative, this model is more like a mix between quantitative and qualitative, since actual data for some components were unobtainable. In essence, the model commences with the emergence of a pavement failure at taxiway Victor (on the left side).

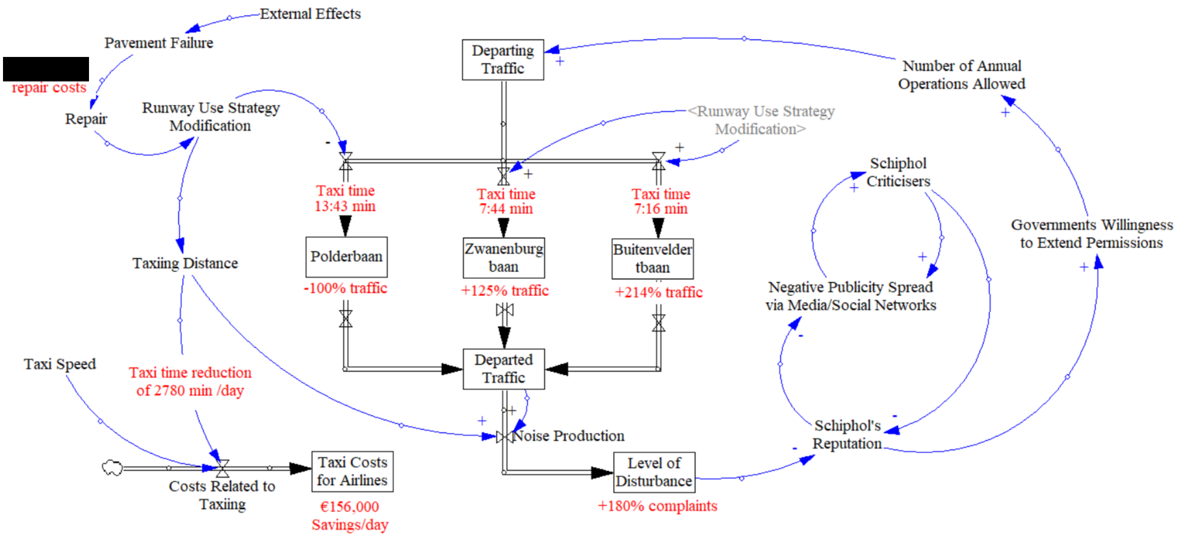


Fig. 5.7. System Dynamics Model of Runway Closure.

5.3.3 Technical Costs Impact of Pavement Failures

The system dynamics model shows that the pavement failure at taxiway Victor had a technical impact, as the failure had to be rectified. Due to this pavement failure, an emergency repair had to take place, consequently the Polderbaan was closed for an entire week [86]. By reviewing organizational declaration forms, the costs associated with pavement failure repairs were revealed. This overview is shown in Fig. 5.8. However, the costs originate from different years, to ensure homogeneity in data, inflation rates for construction projects were derived from the CBS and consequently applied on the prices [87]. Take notice that the rates were applied on the day of repair execution rather than the day of reporting the pavement failure, as there can be some discrepancy between the reporting and execution dates.

In essence, the costs associated with the repairs are depicted for 2017 until 2020, all corrected for inflation. These repair costs include the material and the human resource costs for engineering and execution labor. In general, one can observe that the total repair costs are widely dispersed and skewed. Nonetheless, the majority lies between [redacted] with some outliers. Moreover,

[redacted]

Fig. 5.8. Repair Costs of Pavement Failures.

the average costs are [redacted] for respectively year 2017, 2018, 2019 and 2020. In addition, it also depicts that the technical costs for the pavement failure on taxiway Victor was approximately [redacted] which made this failure the most expensive repair in the recent years. Nonetheless, the costs associated with these repairs still seem trivial when comparing these vis-à-vis with the costs of taxiway or runway maintenance, which can be more than a tenfold greater.

Along with the total repair costs, the required labor hours were attached to the declaration forms. This information is depicted together with the total repair costs in Fig. 5.9. One can observe that in general, that the repair costs increase as the required labor hours increases.

[redacted]

(a) Repair Costs 2017 and 2018.

(b) Repair Costs 2019 and 2020.

Fig. 5.9. Repair Costs of Pavement Failures and Labour.

5.3.4 Operational Availability Impact

Pertaining to the operational availability, it may seem that the closure of the Polderbaan was relatively trivial for Schiphol, because the Polderbaan was rapidly substituted by the Zwanenburg- and Buitenveldertbaan. In the system dynamics model, this is shown in terms of stocks. To actually comprehend how the traffic was distributed to the other runways, again, a flight transponder data file was used. In the same fashion as explained in Fig. 4.10, a data file containing aircraft traffic details for that period was extracted (from 00:01 15 July until 23:59 22 July 2018). Simultaneously, this was done for the same period in 2019 (from 00:01 15 July until 23:59 22 July 2019). The comparison is shown in Table 5.4, it reveals that the traffic on the Polderbaan indeed decreased by 100% in 2018 when compared to 2019. It also shows that the majority of the traffic is diverted to the Zwanenburg- and the Buitenveldertbaan. On the other hand, there is only a small increase for the Kaag- and Aalsmeerbaan. This observation is as expected, as these runways lie in a different direction than the Polderbaan, hence the small discrepancies are possibly caused by the variations in the wind direction.

Table 5.4. Change in Traffic Numbers due to Polderbaan Closure.

Runway Name	Traffic Comparison between 2018-2019
Polderbaan (18R-36L)	100% (-)
Kaagbaan (06-24)	16.6%
Aalsmeerbaan (18L-36R)	16.9%
Zwanenburgbaan (18C-36C)	125.2 %
Buitenveldertbaan (09-27)	214.6%

In general, it is expected that the airport operation was only slightly affected by the closure of the Polderbaan. When considering the traffic numbers in Table 5.4, one can infer that Schiphol preempted a chaotic situation by correctly modifying the runway use strategy. This was done by diverting a large amount of traffic to the Buitenveldertbaan (if the wind direction allowed this), which is normally only used by 6% of the total traffic (refer to Table 4.1). Hence, by optimally using a runway that is underused, the pressure on the Zwanenburgbaan was alleviated and congestion and operational impact was mitigated as much as possible.

At contrary, one may argue that the closure of the Polderbaan has even merits for the operating airlines, because normally it takes a fair amount of time to taxi to the Polderbaan [88]. Hence, substituting the Polderbaan for the Zwanenburg- and Buitenveldertbaan, decreased the overall taxi time significantly. This operational advantage is shown on the bottom left corner of the system dynamics model. By using the taxiway network from Fig. 5.2, the taxi time to the runway holding areas of each of these runways was computed. In essence, the Buitenveldertbaan is the closest runway from Bay D in terms of travel time, closely followed by the Zwanenburgbaan, with respectively 7:16 and 7:44 minutes. The taxi time to the Polderbaan on the other hand, is around 12:39 minutes when traversing taxiway Whiskey 5. Using taxiway Quebec and Zulu would even increase the taxi time to 14:49 minutes. Hence, throughout this week, on average the airlines saved around 6:14 minutes per departing aircraft that would normally go to the Polderbaan, through the decreased taxi distance. This boils down to a decrease of 2780 minutes of taxiing per day on Schiphol (446 aircraft use the Polderbaan on a daily basis, according to Tables 5.1 and 5.2). By referring to the results of Cook and Tanner [81], the savings for diverting the traffic to the Zwanenburg- and Buitenveldertbaan is estimated to be around €156,000 per day. Take into consideration that these are simplified computations and that this is only applicable in this specific situation. Nonetheless it shows the (positive) operational impact when closing off the Polderbaan.

5.3.5 Reputational Impact

Thus far, the impact seems to be positive. However, when considering the reputational damage, the tables may turn. These are represented on the bottom and the right of the system dynamics model. It shows that when traffic is diverted to the Zwanenburg- and Buitenveldertbaan, more nuisance and disturbance is caused in the adjacent urban areas (e.g. Amstelveen). In this event, the biggest sufferers were the inhabitants living adjacent to Schiphol. This was reflected by the number of received noise complaints, which nearly tripled in that particular week [86]. A possible method to quantify the costs of temporal noise nuisance are hedonic pricing models, which express the costs in terms of reduced house prices [89]. However, this would only be valid for areas that are exposed to prolonged periods of nuisance.

The noise complaints weakened Schiphol's position, because the temporal disturbances, which lasted for an entire week, caused a lot of outrage among citizens. The negative word quickly spread across different platforms, which aggravated the situation and generated ample negative publicity. Schiphol has acknowledged in the 2018 annual report that the number of filed noise complaints rose with 40,000 in comparison to 2017, due to the closure of the Polderbaan in July 2018 [90]. With the aircraft transponder data Fig. 5.10 was created, which depicts the flight path of departing and landing airplanes for the Buitenveldertbaan during that specific week. Broadly speaking, it can be seen that there are three main routes. Two routes in the eastern direction that splits up/comes together right above Amstelveen and one route that directly turns to the south. The fact that the majority of the traffic traverses a densely populated area (Amstelveen) already justifies this exponential growth in nuisance complaints. These complaints and the corresponding negative news has harmed the reputation of Schiphol and could have even reinforced the support base of Schiphol criticizers.

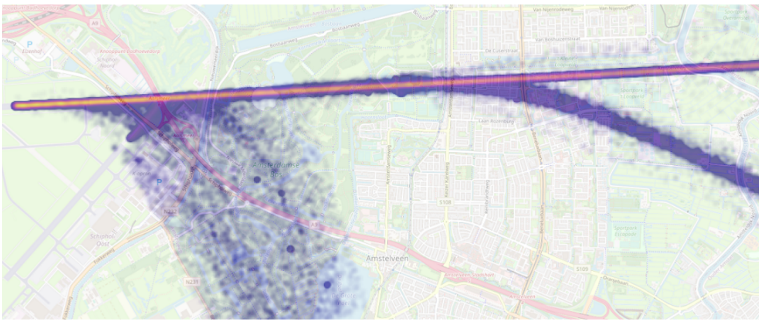


Fig. 5.10. Flight Path of the Buitenveldertbaan.

Considering that the operation of Schiphol is mainly restricted and governed by policies imposed by the Dutch government, reputational damage can lead to substantial impact. Or as Lijesen et al. [89] put it, "like all externalities, noise nuisance may be a reason for government intervention." This may have weakened Schiphol's position during negotiations for operational expansion permits. Ultimately, this event does not only harm Schiphol, but could also have indirect damaging effects for operating airlines. This is reflected by a loop in the system dynamics model, which is connected to the departing traffic stock.

5.4 Chapter Conclusion

The operational impact of pavement failures at different taxiways was quantified by computing the impeded taxi time, when an aircraft has to detour. It was found that the most critical place, where a pavement failure could occur, are some sections of Alpha and Bravo at Schiphol central and taxiway Quebec. The additional costs for detour would be around €80,000 to €90,000 on a daily basis for the airlines.

The impact costs for runways, on the other hand, was qualitatively approached with a case study. Overall, the system dynamics model of the case study was fruitful in showing long-term (rebound) dynamics, which are often difficult to perceive or realize, due to the presence of (lagged) feedback loops. Thus, innocent "trivial" events may cause a cascading dynamic, that can cause more inconvenience than initially thought. Although the reputational impact and the cascading effects are near impossible to quantify, it can be said that it is always larger than the aforementioned (operational) benefits. Otherwise the Polderbaan would not have been the most used runway.

Furthermore, it showcased that the impact of a runway closure can be seen from various perspectives. This is a major aspect to consider when inferring whether the runway closure yielded a positive or a negative impact, and its magnitude. In addition, as one may have noticed, the environmental and safety aspects were not embedded in the system dynamics model. Especially the latter was omitted in the model, as the operational safety remained unchanged. This is because the taxiway section of concern, that was causing an unfavorable situation, was inoperative. The environmental effect on the other hand, can be seen in the light of different perspectives. For example, one may discern between noise and air pollution, however, one could even pose a follow up question like, who is exposed to the harmful pollution or who is incurring it? The environment? A group of residents? Hence, this is a delicate and intricate topic, which deserves an investigation on its own. For now, due to a limited connection with the research objective, it is left as it is. However, it must be stressed that it is undeniable that the extent of environmental impact is altered, simply because the taxi times are shorter and the traffic is directed to other directions, but it is difficult to infer whether it produced positive or negative effects and more importantly, to who?

Lastly and certainly not the least important, it was found that the comparison in operational impact of pavement failures between runways, taxiways and bays is too cumbersome, as each type of asset serves a different function. This for example, leaves the following question unsolved: "what is the difference in operational impact when a pavement failure emerges at the Kaagbaan compared to a pavement failure at taxiway Quebec?" To allow this in the future, a new methodology has to be developed, that can quantitatively weigh the importance of the different asset types in a similar fashion.

Chapter 6

Increased Probability of Pavement Failures due to Deferred Maintenance

6.1 Pavement Failure Probability Choropleth Model

In Chapter 4 a regression technique called the Cox PH model was used to model the relationship between various predictor variables and a dependent variable. The latter entails the emergence of a pavement failure, whereas the former encompasses the aircraft speed, traffic intensity, asphalt layer age and the pavement category. The model ultimately generated a formula that shows how likely a given pavement grid will suffer from a pavement failure based on the specific circumstances. Evidently, as the pavement grid becomes older, the degree of susceptibility becomes more alarming. By combining the information pertaining to the asphalt layer age from Section 4.2, the survival probability for a unique pavement grid can be computed for a given year. For example, an asphalt layer was paved in 2008, hence in 2020 the corresponding pavement grid is in its 12th year. Thus by computing the corresponding survival curve, the probability of a pavement failure emergence in its 12th year can be determined. In the light of the consequences of deferred maintenance, it is of interest to show how this probability increases over time. Or in other words, what is the probability of a pavement failure in its 13th and its 14th year? What if the rehabilitation maintenance is procrastinated from its 12th to its 15th year?

To exhibit this in a comprehensive overview, it was chosen to use a dynamic choropleth. The incentive for this option is that Chapter 4 generated a vast amount of information, which poses the challenge of creating an overview that is extensive, but yet delicate, in the sense that it is also simple to perceive for non-insiders. Since a choropleth is capable of capturing an abundance of details, while expressing a statistical variable through a certain color scheme, this was thought as an elegant solution. In addition, it has the merit that the analyst can easily discern between geographical regions, because the choropleth easily represents variability through colors. In the end, a dynamic choropleth was erected to show how the probability of pavement failures increases for 2018 until 2023 (see Fig. 6.1). In this choropleth, each of the 328 predefined pavement grids has six different states that are determined based on Eq. (4.2). The state alters as a year passes, evidently the state only degrades in time, unless pavement maintenance is conducted. As a side note, it is important to consider that the asphalt layer age is the only time dependent variable, other predictor variables are time independent.

6.2 Choropleth Model Interpretation and Limitation

6.2.1 Choropleth Model Scale Definition

The state of each pavement grid in Fig. 6.1 is based on a numerical value. In essence there were various options to express the state of the pavement grids, for example, the median life could have been used. This median life could then be compared to the actual age of the asphalt layer in a given year. If the actual age surpasses the median life, it means it has a higher chance on failures, depending on how much the median life is surpassed the magnitude of probability is determined. However, this is not a very meaningful indicator, because the number of years that the median life is surpassed is linear in time, how would this subsequently be translated into probabilities? Therefore it was deliberately chosen to exhibit the fraction of similar pavement grids that have theoretically suffered from

Fig. 6.1. Dynamic Choropleth Model Exhibiting the Probability of Pavement Failures (animation is only compatible with AcrobatReader, PDF-XChange, Acroread or Foxit Reader. Static figures are found in Appendix G).

a pavement failure (cumulative probabilities). For example, Fig. 4.22a shows the survival function for an average pavement. It shows that there is a 63.9% chance to have a failure free (average) pavement grid that is 12 years old. This also implies that 36.1% of the grids, that are exposed to the same circumstances, would have failed by then. The merit of such an indicator, is that it is probabilistic and easier to comprehend for analysts. The analyst can shape their own perception and deductions, based on the provided facts. Evidently, the probabilities are different for each grid, since each is exposed to different circumstances.

For the choropleth in Fig. 6.1, six groups were defined with a color palette ranging from green to red, to exhibit how the state of each unique pavement grid alters between 2018-2023 based on the aforementioned probabilities. Take notice that certain sections are filled up with light blue lines, these are concrete sections or sections that are outside the demarcations of Parcel one. The six groups are defined as follows, 0-25%, 25-50%, 50-65%, 65-80%, 80-90% and 90-100% (take notice that the groups get narrower). These defined groups or the color scheme can easily be altered, the input of the model on the other hand, is more difficult to amend. This is due to the fact that different software platforms were used, which are not interoperable. The shown percentages indicate the fraction of similar pavement grids that have failed before a given moment in time. Evidently, a new asphalt layer will commence in the former group, as time passes it will slowly progress to the next state. This process is certainly not linear, because in the former years the pavement grids prove to be more durable. This aligns with Fig. 2.1 adopted from [12]. Without any intervention, the grids will all end up in the red state (when the grids are perpetual). This makes the grids monochrome which has little use, therefore the grids that have been replaced between 2018-2019 or will be replaced in 2020 are set back to zero at the moment of intervention. The planned maintenance beyond 2020 will not be taken into consideration in the choropleth, as these projects may be subject to change. Therefore it is essential to show the corresponding probabilities of pavement failures, to support the maintenance prioritization process if decision makers insist on deferring maintenance.

6.2.2 Choropleth Model Interpretation

The choropleth model in Fig. 6.1 yields a straightforward overview that highlights where pavement failures have an increased probability to emerge. The used indicator is a cumulative probability that shows what fraction of the similar pavement grids have theoretically suffered a pavement failure. It is important to consider that the term "similar pavement grids" is used, because each grid is unique and behaves differently. Hence, despite intuition tells that some sections should have the same color, it is often invalid as there are non-apparent differences that provoke these differences. For example, runway Polderbaan consists of nine similarly sized grids that were erected in 2003. Yet they are different. For example, at the head of 36L many aircraft stand still. Or the touchdown section and the section between the first and the second exit, that were replaced in the past years. Hence, they all possess different characteristics, although it is not always evident. The differences at the straight taxiway sections of Zulu are even less apparent, because they are similar in terms of number of movements, asphalt layer age and at none of the sections, stationary aircraft were identified. Yet, there are minor differences, for example the aircraft speed, at which the traffic traverses the sections. However, these differences are near negligible and did not provide an output that is significantly different.

Regarding the main objective of this research, this choropleth is fruitful for a plethora of uses. Most notably, the merit of this dynamic model is its simplicity in exhibiting the quantification of the consequences of deferring maintenance. Although unsuccessful endeavors were made to monetize these consequences, this model still shows how the probability of pavement failure occurrence increases as the asphalt layers become older. Moreover, the probability on a pavement failure is not linearly increasing, but accelerates in a latter stadium. This reflects that deferring maintenance goes hand in hand with an increased chance in pavement failures. Furthermore, this model really differentiates itself, by recognizing that each pavement grid behaves differently and that under certain circumstances the chance of pavement failures are even further increased. For example, taxiway Yankee is underexploited, whereas taxiway Whiskey is excessively used by aircraft. If they were paved in the same period, would it make sense that the chance of pavement failures is equal for both taxiways in a given year? To make the point clear, each pavement grid is subject to different dynamics, thus it would do no justice to consider them in the same way. This model incorporates nontrivial variables to capture these dynamics and hence, some areas will transit quicker from one state to another.

6.2.3 Choropleth Model Limitations

As mentioned earlier, the initial line of thought was to erect a risk model based on the likelihood that a pavement failure emerges, from Chapter 4, and the impact of a pavement failure as described in Chapter 5. Unfortunately, it was not possible to accurately quantify the operational impact of a pavement failure at the runways. Hence, the impact of a pavement failure at the runways was merely approached qualitatively. This renders it impossible to accurately compare the magnitude of impact of a pavement failure on a runway and a taxiway, let alone the comparison of two different runways. Without this comparison, the impact cannot be visualized, therefore it was deliberately chosen to omit the operational impact in the choropleth shown in Fig. 6.1, as it would heavily impair the efficacy of the model. This issue will be further elaborated in Section 6.3.

Furthermore, the choropleth model has the demerit that some pavement grids belong to two different asphalt layers. Or in other words, some pavement grids are on the boundary of two asphalt layers that were paved in a different period, hence these grids belong to two asphalt ages. This issue was inevitable as it was a trade-off between various aspects. First of all, the grids were earlier categorized based on their type (e.g. junction, straight or runway). The same issue was encountered here, as some junctions would belong to different asphalt layers. In this case, the priority was given to the categorization according to the type and to neglect that a small fraction of the grids would fall into two layers. This automatically meant that some of the grids in the choropleth would also be on the boundary of two asphalt layers. Secondly, the pavement grids had to be similar in size, because the size of a grid affects the probability of a pavement failure (i.e. a larger surface means a higher chance on failures). An option was to decrease the size of the pavement grids, however this would radically increase the complexity of the model. Moreover, this would conceivably generate insignificant statistical models, which is actually the backbone of the model in the first place. Thus, some accuracy was sacrificed to make the analysis feasible.

Lastly, as mentioned repeatedly, some of the predictor variables are not time bound. This is due to a lack of data, as not everything has been correctly stored from the beginning. Time independent variables provoke certain implications and should not be completely disregarded, despite there are no remedies to bypass this deficiency. For example, currently it has been assumed that the number of movements that traverses a taxiway section remained equal from the beginning until now, which does not always hold true. This introduces a limitation that affects the accuracy of the model, the only way to overcome this is to keep better track of this data and refresh it at a yearly basis.

6.2.4 Choropleth Model Validation

Processing the data to erect the dynamic choropleth model was done carefully to prevent any errors. In addition, the input data for the Cox PH model and the corresponding outputs were checked twice. These in- and outputs are illustrated in Appendix G, which includes all the attributes that belong to each pavement grid and the projected probabilities that were used for the choropleth model.

Yet, regression models are seldom capable of justifying all the occurrences, which is known as a standard error [91]. It is also anticipated that this is the case for the created choropleth, since the airport pavement is subject to a large amount of dynamics. When projecting the pavement failures that emerged in 2019 on the dynamic choropleth model, it becomes evident that a number of pavement failures are not explained by the model. There may be several reasons, because the pavement is subject to different operational and environmental conditions, which inherently cause variation. For instance, sporadically, a lightning strike produces a pothole or fuel is accidentally spilled, which decreases the integrity of the asphalt [92]. These are factors that cannot simply be captured through the inclusion of other variables, hence a standard error will always persist. Furthermore, it appears that especially the bay areas are biased and that the majority of the failures emerged in bay EF, DE and CD. Possibly, this is justified by a combination of heavy aircraft that are turning and traveling slow, since heavier vehicles generally inflict more damage on the pavement [93]. This demonstrates that more research is required, for instance, the identification of the failure type, which may help to further enhance this model. This will be further discussed in the discussion.

6.3 Pavement Failure Risk Choropleth Model

Despite Fig. 6.1 did not shed light on the impact of a pavement failure together with the likelihood, the former can still be exhibited separately. By deriving information from Fig. 5.5, the map in Fig. 6.2 was created. It exhibits where the impact of a pavement failure would be the largest. Recall that the information in this figure is identical to Fig. 5.5, it is merely projected in a different manner.

[redacted]

Fig. 6.2. The Operational Impact of Pavement Failures.

In this figure it becomes evident that a pavement failure would have the highest impact at the taxiways in the heart of Schiphol's taxiway system (e.g. Quebec, Alpha and Bravo). It is peculiar that not all taxiway sections of Alpha and Bravo are subject to the same extent of impact. This is caused by the fact that, at some gates, more aircraft are arriving or departing than at other gates. Thus, if a pavement failure would emerge in the vicinity of that gate, more aircraft would be affected. Another interesting observation is that taxiway Yankee and Zulu fall in the same impact category. The reason is that neither taxiway Yankee nor Zulu are the fastest path to the Polderbaan. On the other hand, if taxiway Whiskey would be closed it has a higher impact, as this is the fastest path to the Polderbaan for the majority of the fleet (depending on the departure point).

To create a similar overview for runways, the computed revenue streams from Section 5.2.4 can be used to reflect the importance of each runway. Or in other words, the extent of impact when a runway is closed off due to a pavement failure. In addition, the risk can be determined by combining information pertaining to the impact and the likelihood. To attain this, a standard risk-matrix, that discerns between low, medium, high and very high risks, is adopted from [94]. This matrix is depicted in Appendix H. In this matrix, there are four risk classes that can be used to classify each runway section. The degree of risk is the product of the extent of impact of a pavement failure at the given runway and the likelihood of a pavement failure in the given section. More specifically, a runway section can be placed in five different "impact" classes and five different "likelihood" classes. To allocate the impact class to each runway, a min-max normalization is applied. To exemplify, Section 5.2.4 shows that the maximum generated revenue stems from the Kaagbaan, conversely the lowest comes from the Buitenveldertbaan (respectively €149 million and €22 million). In this normalization technique, a one is assigned to the former and a zero to the latter. The revenues of the remaining runways get transformed into a decimal between 0 and 1. This numerical value determines the place of the runway on the impact dimension, when its equally divided into five equal portions.

Fig. 6.3. Dynamic Choropleth Model Exhibiting the Risk of Pavement Failures for Runways (animation is only compatible with AcrobatReader, PDF-XChange, Acroread or Foxit Reader).

To determine the likelihood class for each runway section, Fig. 6.1 was used. Take notice that the likelihood of a pavement failure is not identical for all the sections within a runway. In addition, the likelihood is affected by a time variable, whilst it is assumed that the impact remains unaffected.

After defining how the risk of a runway section is classified, the model in Fig. 6.3 was erected. It shows how the risk is altering as time passes. It imperative to mention that the risk cannot increase significantly, if the given runway scores low on one particular aspect. On the other hand, if the impact is high or very high, it would mean that, under no circumstances the risk can low.

One of the most important deductions from this model, is that especially the Polderbaan has an increased risk. Ultimately, this also becomes true for the Kaag- and Aalsmeerbaan. Although for the latter two, only particular runway sections pose an increased risk, it is important to realize that if one section poses a high risk, it is actually for the entire runway. As all sections of the runways must be operative to fulfill its function.

6.4 Chapter Conclusion

This chapter elaborated on the magnitude of risk associated with deferred pavement maintenance, by combining the insights from Chapters 4 and 5. The generated output was processed into a dynamic choropleth, that exhibits the probability of pavement failures. It depicts how the probability of pavement failures increases over time for some sections and simultaneously decreases for other sections, as pavement maintenance is conducted. The merit of such a model is that it captures all elements and is transparent and easily perceivable by all analysts.

Chapter 7

Conclusions and Recommendations

This chapter will enumerate the most important insights and comprehensively respond to the research questions with the results from the preceding chapters. To do so, this chapter has been divided into three sections, namely the discussion, conclusion and recommendations. The former will emphasize on interpreting the results, address the limitations and reflect on the overall contribution. On the other hand, the conclusion will concisely synthesize the results and restate the most important findings. Finally, the concluding section will elaborate on recommendations for future research by looking further ahead. However firstly, a restatement of the main objectives that have been formulated to respond to the identified research problem:

> "
> 1) First of all, to identify the rationales for deferring taxiway and runway pavement maintenance at Amsterdam Airport Schiphol. 2) And secondly, to investigate the consequences of deferring taxiway and runway pavement maintenance for the risk of pavement failures, to support the maintenance project prioritization process for decision makers of Amsterdam Airport Schiphol and Heijmans.
> "

7.1 Discussion

7.1.1 Managerial and Scientific Implications

In Chapter 3 it was found that several rationales may lead to the unfavorable decision to defer pavement maintenance. This phenomenon is inevitable and will always persist. This can be seen as a complex problem, or as GM Winch [95] would put it: "a wicked problem". Wicked problems have innumerable causes, morph constantly, and may never be solved definitively. Fortunately, these problems can be tamed. Or in other words, the notion of this research was not to overcome the problem of deferring pavement maintenance, but to adequately deal with the situation at hand. However, to administer these situations properly, it was necessary to delve into the matter to fully comprehend the circumstances. Therefore, this research endeavored to investigate the long-standing topic of the consequences of deferring taxiway and runway pavement maintenance, to obtain more knowledge about this phenomenon in order to deal with it accordingly in the future.

Upon generating research outputs, it was of essence to present it in an elegant manner, to make it straightforward to perceive for everyone. Therefore, the results were handled delicately and processed in a choropleth model, which is an effective tool to geographically present complex statistical results. This choropleth model gives a clear overview of the pavement sections that have an increased chance of pavement failures. And since this model is a function of time, it also provides insights for the forthcoming years. Thus, decision makers from Schiphol and Heijmans can exploit this model to prematurely conceive or alter the maintenance strategy and prioritize the maintenance projects, when deemed necessary. However, this research was not only fruitful for the decision making process for pavement maintenance on Schiphol, but has a much wider applicability. For instance, it generated an abundance of knowledge about how different parameters may accelerate or stagnate the development of pavement failures and thereby indirectly the pavement deterioration. This puts a question mark behind the current maintenance strategy, wherein pavement sections are rehabilitated based on a certain time interval. Should pavement sections, that are subject to different dynamics, be treated in a similar manner? Or to put it more in context, should taxiway Victor and taxiway

Yankee be maintained at the same interval, while considering that the former handles more than ten times the traffic of taxiway Yankee? For the same reason, aircraft engines are checked based on flight hours, rather than a monthly or yearly interval. However, a tailored maintenance plan at this level of detail, is easier said than done and will require more research about how the pavements actually deteriorate.

Then related to whether these results can be generalized to other airport pavements. Frankly, due to the versatility of the regression model, it is certainly possible to some extent, but some remarks have to be noted here. Firstly, the same type of data has to be acquired for other airports and the pavement sections have to be categorized in a similar fashion. However, the area that is debatable, is how climatic factors contribute in the development of pavement failures. Evidently, other airports are subject to different weather circumstances. For instance, Mexico Airport is located 2200 meters above sea level, the air is thinner at this altitude and so is the barometric pressure. Or Dubai International Airport, where the mercury regularly touches 45 degrees Celsius. Thus the results derived in this study are not a fixed recipe, however the deployed research methods can be replicated to investigate the same phenomenon, given that data is available. And albeit this research predominately emphasized on airport pavements, nonetheless, these methods can also be used to analyze other pavement related issues.

Furthermore, this research also inquired into how MJOP plans are reviewed by Schiphol and subsequently provided a stakeholder analysis. Heijmans, as the main contractor, can use these extensive insights in the initial stages of MJOP conception, because the analysis has revealed the key points that are especially reviewed by Schiphol. In addition, the identification of the most pertinent stakeholders shows which entities should be intensely involved in the MJOP conception process to enhance the efficacy and thereby the success of these plans.

Then regarding the scientific implications of this research. Initially, much was unknown about this topic, especially for airport pavements, as shown in the literature review. Studies seldom touched upon this topic in combination with airports, with the exception of a few. However, they did not quantitatively address the consequences of deferred pavement maintenance, but mainly provided general and qualitative descriptions of the consequences. This research however, fills this knowledge gap by quantitatively showing that deferred pavement maintenance on Schiphol will go hand in hand with an increase in pavement failures. Moreover, it quantified how different important influential factors play a role in the emergence of pavement failures and to what extent. Lastly, it also investigated the magnitude of operational impact that a pavement failure can cause across taxiways and runways. These operational impacts have implications that extend far beyond the technical costs.

7.1.2 Research Limitations

As mentioned in the preceding section, a limitation of this research is that the results are tailored to the situation of Schiphol Airport and cannot be directly generalized to other airports. Furthermore, the locations of the pavement failures were determined based on qualitative descriptions, since accurate records are not available. To mitigate the margin of errors in pinpointing the failure location in terms of GPS coordinates, workorder and declaration documents were scrutinized to enhance the accuracy of the locations. Frankly, despite these efforts, interpretation errors will always persist. Hence, when perceiving the results, one should be aware that the numbers are subject to small errors. Furthermore, since the descriptions of the pavement failures were not accurately enough, this research did not delve into matters that relate to how pavement failures actually emerge. Only the circumstances under which the pavement failures tend to emerge, were investigated.

Secondly, asphalt layers are replaced sooner than an analyst would want and throughout the life cycle of such a layer, several curative maintenance interventions will be conducted. Pertaining to the former, in the ideal case, the asphalt layer should remain for a prolonged period of time to understand how the pavement behaves beyond the normal maintenance intervals (e.g. 20, 25 years). In the status quo, the pavements of Schiphol are rehabilitated at an interval of approximately 15 years, thus only sporadically there are layers that are 18 or 20 years old. However, since this is seldom, there is insufficient data about the behavior of layers when it becomes older than, let's say 17 years. Predictions based on little or no data, may impair the reliability of predicting the failure occurrence on layers older than 17 years old. Then related to intermediate maintenance interventions, although it is inevitable, the chosen maintenance strategy can affect the results. Evidently, it would pose no threat when the applied approach is constant over time and fixed for each asset. However, practically speaking, this is not attainable. Thus when interpreting the results, the intermediate maintenance interventions should also be considered.

Thirdly, it was found that the dynamic choropleth model was not capable of fully justifying the pavement failures. Conceivably, this is caused by the absence of missing parameters. Despite the model is heading into the right direction, there are still missing pieces. This stresses the necessity of future research to further enhance the model. For example, by involving a variable that can characterise the weight or the type of aircraft, that is passing the pavement sections. Moreover, it was earlier addressed that a large fraction of the pavement failures emerged in the bay areas. However, it appears that they are unequally distributed. This indicates that more refinements will be needed and that simply categorizing all the bay sections into one category is insufficient.

Lastly, in the operational impact analysis, the effects of traffic congestion were not considered. Currently it was assumed that there is ample capacity and thus the traffic could traverse each section seamlessly. For example, when taxiway Bravo would be closed, traffic could use taxiway Alpha. However, this would go hand in hand with more traffic congestion and waiting times, which would further induce the operational impact. To model this, different simulation approaches have to be used. A possible alternative is to use stochastic discrete event simulations, because it incorporates the queue theory to model the effects of congestion and waiting times.

7.2 Conclusions

This research attained both objectives successfully and furthermore provided a plethora of insights that are not only meaningful for Schiphol and Heijmans, but may contribute to the existing knowledge base and therefore have a wider applicability. In this section, the most pithy points will be enumerated to provide an accurate and thorough impression of this research.

The main body of this research commenced with Chapter 3, which aimed at investigating the incentives for deferring taxiway and runway pavement maintenance. The thematic analysis of the qualitative data from the interviews with Schiphol and Heijmans insiders, demonstrated that especially the attainability and financeability pillars are often the reasons for deferring taxiway and runway pavement maintenance. Most notably, the financial and operational restrictions. The former can be the result of a contracting economy or other (development) projects that are competing for the financial resources. On the other hand, the latter is regularly imposed by the OPS department, because some maintenance projects are too large with respect to the spatial scope. This indicates that stakeholders, other than the ASM department and Heijmans, can exert considerable influence on the MJOP plans. Hence, it is pivotal to prematurely consider these stakeholders in the conception of maintenance plans.

In addition, through scrutinizing organizational documents in Chapter 3, it was found that deferment of pavement maintenance projects takes place twice a year on average and that projects are usually deferred by one to three years. This reflects that deferring maintenance is a topical and recurrent topic and again stresses the necessity of identifying the consequences of such decisions. Thereafter in Chapter 4, the reported pavement failures were analyzed with a statistical model to reveal how deferred pavement maintenance contributes in the development of pavement failures. In addition to the time variable, also other pertinent parameters were incorporated in this analysis. These parameters encompass the number of traffic and the speed at which aircraft would pass a certain pavement section, the characteristics of the pavement foundation, the pavement section category and the extent to which the given section is subject to static loads. Together with the date at which the pavement sections were paved, the pavement failures, that emerged on the pavement of Parcel one, were analyzed with the statistical Cox PH model. The output of this special type of regression is in the form of a survival curve, that shows the probability that a given pavement section will survive or be pavement failure free for a certain period. The efficacy of this model, is that it allows the evaluation of the influence of pertinent parameters. This showed that the indicator of the pavement foundation, the surface deflection, had no or merely a negligible influence on the survival curve. A higher traffic intensity and more static loads, on the other hand, appear to have a negative impact on the survival curve, i.e. pavement failures tend to emerge quicker on sections that are subject to these circumstances. Conversely, a higher aircraft speed seems to be advantageous for the pavement sections, conceivably because the load duration is shorter. Furthermore, the bay areas and junctions seem to be more susceptible to pavement failures, as the majority of the failures emerged in these regions. A possible explanation is that these areas are subject to different types of loads that are provoked by braking, pushback and turning maneuvers. Then for runways, a peculiar result was discovered, namely that only a limited number of pavement failures emerged on the runways. This aligns with the findings from Hveem [45]. It is plausible that the anti-skid layer atop of the asphalt layer makes the tarmac more robust. On the other hand, landing airplanes roll at a high speed, thus the loading phenomenon is transient and less severe due to lift forces created by the wings of the aircraft [70].

Now pertaining to the most important aspect, the survival curves were time dependent and proved indeed that pavement failures tend to emerge on older asphalt sections. For example, the analysis exhibited that 12-year-old pavement sections have double the chances to incur a pavement failure compared to an 8-year-old section. This conclusive evidence proves that deferring taxiway and runway pavement maintenance is inextricably intertwined with an increased probability of pavement failures. This aligns with the findings of the study by Yurchenko [17], who inferred that most of the moderate and heavy cracks on the pavement of Schiphol, tend to form at sections older than seven years. Thus, maintenance projects for the pavement sections, that pose the highest level of risk, should be prioritized to mitigate the probability for failures. Furthermore, the consequences of deferring taxiway and runway pavement maintenance for sections that are younger than 10 years, has little consequences. However, it will increase over time as the pavement sections approach its 10th or 15th year of existence

After these extensive insights, endeavors were made in Chapter 5 to quantify the operational impact of pavement failures. The operational impact analysis for taxiways was conducted with a taxiway network. By applying the fastest path principle, the impeded taxiing time was compared to the unimpeded taxiing time to compute the extent of traffic detour due to a pavement failure on a given pavement section. It showed that pavement failures on certain sections of the Alpha and Bravo taxiways and taxiway Quebec will lead to the highest impact, with detour costs of up to €90,000 on a daily basis. Conversely, the quantification of the operational impact of a pavement failure on a runway, proved too cumbersome. Therefore it was merely qualitatively approached with a case study of the Polderbaan closure of 2018. This case study exhibited that the airlines saved around €156,000 a day, because all the airplanes were diverted to other runways that are much closer to the gates. In addition, the case study also showed that reputational damage could have a detrimental effect in the long-term, due to rebounding dynamics. Due to the Polderbaan closure, the number of noise complaints increased by 40,000, compared to the preceding year. This may be an incentive for the Dutch government to intervene by imposing restrictions on the operation of Schiphol [89]. If this would materialize, it could have devastating effects.

Ultimately, the insights from Chapter 4 were used to erect a dynamic choropleth model that exhibits how the probability of pavement failures, across different pavement sections, alters as a function of time. Unfortunately, the operational impact was omitted herein, as it would impair the efficacy of the choropleth model. This is because the different pavement sections are heterogeneous in terms of function. For example, how can a runway, taxiway or a bay section be accurately compared? Within the available time frame it was not feasible to develop a framework to effectively measure their respective importance for Schiphol and to subsequently incorporate it into the choropleth model. Nonetheless, this dynamic model gives a clear overview of all the pavement sections that are in the right circumstances for "breeding" pavement failures. In addition, it also exhibits the pavement sections that pose a lower level of threat, if maintenance projects must be prioritized, these projects should be first in line for deferment.

7.3 Recommendations and Future Research

This research has dealt with various aspects of pavement failures and the airport operations. As the research progressed, new promising ideas arose for certain data sets or topics, which could offer a window of opportunities for new research directions. Although not explicitly investigated, this research has laid a foundation for the topics that have potential to be the subject of future research. This section will therefore devote attention to recommendations for both Heijmans and Schiphol, which will be followed by an enumeration of potential research directions for future works.

7.3.1 Recommendations

- Section 1.4.1 briefly touched upon the fact that maintenance decisions, made by Schiphol, may have implications for Heijmans, since they are engaged in a performance-based contract. At the time of writing there was a knowledge gap, however through this research, ample knowledge about this matter was acquired. As addressed in the preceding chapters, deferred pavement maintenance is linked to a higher chance of pavement failures. This implies that the decision to defer pavement maintenance may lead to unfavorable situations for both Heijmans, as main contractor, and the asset owner, Schiphol. As mentioned before, the performance-based contract stipulates that Heijmans receives a periodical standard fixed fee to guarantee the performance of the pavement assets within the demarcations of Parcel one. However, as Schiphol insists on deferring pavement maintenance, the chance for pavement failures increases, which transfers more risk to Heijmans (main contractor). This produces a conflicting objective, because on the one hand, Schiphol has the desire to defer pavement maintenance, whereas Heijmans has the objective to mitigate the risks of pavement failures to fulfill the contractual obligations. In an act to overcome or pre-empt these state of affairs, an additional clause was appended to the contract, which gives Heijmans the option to locally withdraw from the existing contract. In such situations, the latter cannot be held financially accountable nor liable for the particular pavement section. Hence, the identified consequences of deferring pavement maintenance will be predominantly a burden for Schiphol. However, the size of the burden is difficult to accurately identify, due to the intrinsic stochasticity of the emergence of pavement failures. Thus, it is intricate to exactly pinpoint which of the pavement failures are caused by deferred maintenance or would have emerged either way. Either way, there is conclusive evidence that underpins how the chance of pavement failures increases as the life cycle of the pavement layers are extended due to deferred maintenance. These insights, in combination with the information about the impact that pavement failures can provoke, should be carefully considered when deciding to defer pavement maintenance in the decision making process. The question that should be posed by Schiphol is: Do the benefits of deferring pavement maintenance, for whatever reasons, weigh up to an increased chance of pavement failures? While considering that a pavement failure can lead to catastrophic effects, like the closure of taxiways or runways as shown in Chapter 5.

- In Chapter 3 it was identified that pavement maintenance is deliberately postponed at regular intervals and that limited financial resources are often the culprits. In such cases it is pivotal to effectively leverage the available resources, while limiting the corresponding risks. Or in other words, if projects must be deferred due to financial deficits or other rationales, the most critical maintenance projects should be materialized first and the projects that involve less risk should be deferred. To attain this, it is necessary to differentiate between the risk of pavement failures for different pavement sections, in terms of impact and likelihood. This can be accomplished due to the fact that each pavement section is exposed to different dynamics, thus the corresponding risks will differ from section to section. To exemplify, see the schematic overview in Fig. 7.1.

  In this simplified scheme, four fictive maintenance projects are depicted. These projects aim to rehabilitate the asphalt layer at certain pavement sections. These pavement sections are exposed to different characteristics or variables, more specifically, the pavement age, number of traffic and the speed at which they traverse the given section and the type of section. In a traditional multi-criteria analysis, weights will be applied to each of these variables and ultimately the score will be determined for each alternative. However in this research, these weights and the corresponding scores are already processed and consequently summarized with a numerical value in Fig. 6.1. Hence, it highlights the most critical pavement sections that pose a higher risk of pavement failures. The highlighted sections are predominantly old pavement sections, where many aircraft cross with a low or no taxi speed, and hence should be closely monitored. Thus when new maintenance plans are erected, these sections should be prioritized. An example are taxiway Yankee and Quebec, both were erected in 2005, however, the latter is used much more extensive than the former. Moreover, Fig. 6.2 showed that a pavement failure at taxiway Yankee is less alarming for the airport operation than a pavement failure at taxiway Quebec, as the latter is one of the most important taxiways at Schiphol. Furthermore, not only the number of traffic should be considered, also taxiways that involve

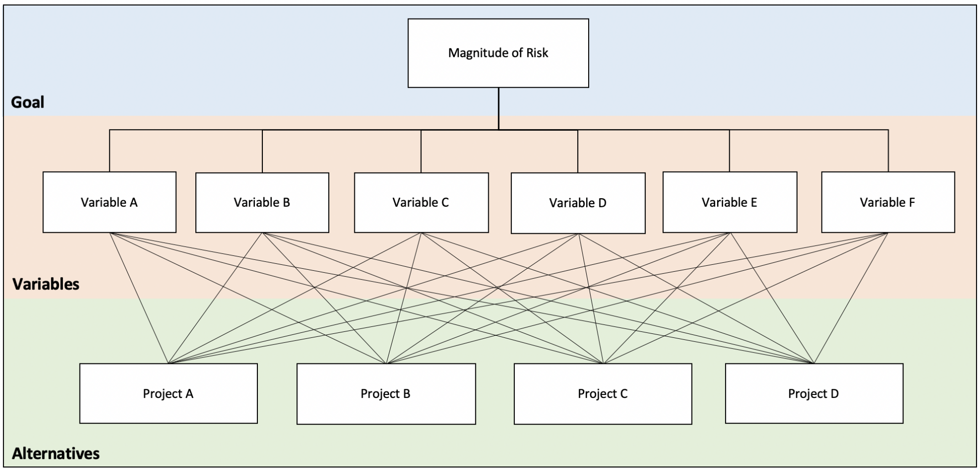


Fig. 7.1. Schematic Overview of Risk per MJOP Project

junctions, are subject to a higher risk of pavement failures. Therefore, these sections also fall in a higher risk class. Especially the junctions at A21-A22, A20, A26-A27 and Point Pieter pose a higher risk, since these junctions are very important in terms of the operation as shown in Fig. 6.2.

- Throughout this research, several challenges were encountered that relate to the way data is stored. These deficiencies hampered certain processes in this research, but can be pre-empted in the future. For example, it was found that the records of the pavement failure data was far from ideal. Despite best attempts to accurately pinpoint the locations of the pavement failures, it could not approach the exact location. Hence, these details should be recorded more accurately in the future, most notably the location where it manifested. For instance, at regular intervals, the location of the pavement failure was indicated through a google maps picture, indicating its exact location. However, this was done far too inconsistently, as this was only the case for a handful of occurrences. Take the surface deflection measurements as an example, the exact location of where the measurements were taken are documented and digitized through GIS. Ideally, in a similar fashion, this should be done for the pavement failures. This will offer new and interesting opportunities, like the option to discern between failures that emerged in the vicinity of the centerline and failures that emerged in the shoulder area. This provides the option to analyze how the environment may contribute to a pavement failure, without the influence of traffic loading. This seems more like a consistency issue, as it is already done sporadically. Hence, it would require no radical alterations in the current processes to consider this.

- This recommendation complements the previous recommendation, as this also pertains to the procedure of storing data. On top of the location of where a pavement failure emerged, the pavement failures should also be classified based on the type, size, severity and if possible, an explanation of the failure cause. This will help to further enrich the model to predict pavement failures and to assess which types of failures tend to emerge under what circumstances. Furthermore, it gives the opportunity to eradicate the pavement failures from the data set that are caused by chance and have nothing to do with the condition of the pavement itself. For example, pavement failures that are caused by a lightning strike. A straightforward solution to this and the preceding issue, is to introduce a standard "pavement failure form" with checkboxes or preselected answers, that is mandatory to be filled in by the responsible pavement engineer. This form is a mnemonic to remind pavement engineers to provide this information, moreover it ensures that the given information is uniform, regardless of the evaluator.

- Finally, it is recommended to replicate the statistical analysis, but then for the pavement condition. The reasoning of this notion is that the pavement failure data set is discrete data and more subject to variability than for example the PCI score of different pavement sections. A continuous indicator such as the PCI would be more accurate as the degradation trend can be analyzed. Furthermore, despite it will cost more effort, the PCI provides a better idea of the pavement section state than details about pavement failures, as the latter is more locally. Or in other words, a pavement failure does not necessarily mean that the entire section is compromised, whereas a low PCI value does summarize the state of an entire pavement section into one numerical value. In addition, the survival analysis is very versatile in terms of applicability, thus it is recommended to use the survival analysis on other objects within Parcel one, such as light bulbs or power cables. These light bulbs can be differentiated based on the bulb type, shape, size and location [96] and power cables based on manufacturer and low/medium and high voltage cables [97].

7.3.2 Future Research Directions

- In Chapter 4 it was addressed that the bay areas and the junctions are more susceptible to pavement failures. It is anticipated that the intricate combination of the pushback and braking maneuvers and the low taxiing speed are the major contributors in the development of a pavement failure in the bay areas. However, conclusive evidence is still absent and more research is required to validate this hypothesis. This would also help to enhance the erected model, as the prediction accuracy in the bay areas are not at the desired level. Thus by incorporating this as a variable, it is excepted that the accuracy of the model can be improved.
- The discussed flight transponder data in Chapter 4, has a myriad of applications for pavement related analyses, but has also operational uses. For instance, it can be used to identify the locations where aircraft tend to turn or to initiate the braking maneuver. However, the transponder data would have to be manipulated to a finer level. For example, a prudent course of action would be to identify all data points corresponding to one unique flight, which are then combined to forge a line representing its flight path. This will exactly exhibit where aircraft are turning (wringing traffic). Afterwards, the identified hot spots can be linked to the pavement failures data, or alternatively, to the pavement condition. In addition, these flight paths may be transformed into taxi speed profiles, which depict the aircraft speed along the route. This may precisely show where aircraft accelerate/decelerate. This investigation may help to understand the effects of wringing traffic and the braking maneuvers.
- An operational applicability of the transponder data is to use this data to scrutinize the current layout of the taxiways and runways of Schiphol Airport. As Fig. 4.19 has shown, there are places with queues that provoke congestion at adjacent taxiways. Most notably, this is the case for the head of runway 24 and runway 09. By utilizing the provided information, the use of runways can be optimized to mitigate traffic congestion at adjacent taxiways. This can also save costs, as Chapter 5 demonstrated that delay has a considerable price tag.
- As addressed earlier in the limitations, the operational analysis of Chapter 5 did not consider traffic congestion. Future studies could fruitfully explore how the operation would be affected by pavement failures, with for example discrete event simulations. This simulation technique incorporates the queue theory and is therefore a suitable method to capture the effects of congestion in all types of situations. In addition, a (universal) method to weigh the importance of different assets such as runways and taxiway should be developed. These insights could then be consolidated with the likelihood of pavement failures, to determine the risk. This can be added to the model in Fig. 6.1, to extend it.

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Appendices

Appendix A

Types of Pavement Distresses

Type of distress	Cause	Type
Alligator cracking: Repeated loading links the series of parallel cracks to alligator cracks. Alligator cracking occurs predominantly in the wheel paths.	L	S
Bleeding: Sticky bitumen is the result of bleeding. It occurs during hot weather when asphalt fills the voids of the bitumen and expands out onto the surface.	M	F
Blocks cracking: Block cracks are larger than alligator cracks. It is mainly caused due to daily temperature cycling and shrinkage. Its source of error is material and environmental factors.	CL	F
Depression: Elevation in the pavement, caused by settlement of the foundation soil. It may cause hydroplaning.	Cons	F
Corrugation: Ripples occurring at regular intervals along the pavement perpendicular to the direction of traffic. Caused by traffic and unstable pavement surface or base.	M	F
Jet blast erosion: Bituminous binder will be burned or carbonized, causing darkened areas on the pavement.	Op	F
Joint reflection cracking from PCC: Caused when asphalt overlay on PCC slabs and is produced by the movement of the PCC slab beneath the surface due to loads, thermal and moisture changes.	CL	F
Longitudinal and Transverse cracking: These types of cracks are not associated with loading. This is mainly caused by construction, material and environmental factors. Provoked by poor construction, shrinkage due to low temperatures or hardening of the asphalt and a reflective crack caused by cracks beneath the surface course.	CL	F
Oil spillage: deterioration or softening of the pavement surface.	Op	F
Patching and utility cut patch: A patch covers a defect, nonetheless it is still considered a defect. Traffic load, material and poor construction practices can cause such patch deterioration.	Other	F
Polished aggregate: caused by repeated traffic applications. The surface binder is worn away to expose coarse aggregates, this impairs skid resistance.	M	F
Raveling and weathering: Wear of the pavement caused by dislodging of aggregate particles and loss of asphalt binder leads to raveling and weathering. This may produce severe FOD.	CL	F
Rutting: rutting is a longitudinal surface depression and occurs due to permanent deformation, which is predominantly caused by lateral movement of the materials due to traffic loads.	L	S
Shoving: Longitudinal displacement caused by braking and turning aircraft.	M	S/F
Swell distress: caused by frost action in the subgrade or by swelling soil.	Other	F
F= functional; S= structural; M= materials; Op= operations; CL= climate		

Fig. A.1. Pavement Distress Types.

Appendix B

Interview Strategies and Transcripts

B.1 Interview Strategies

An interview is a data collection method that allows the researcher to collect a wide variety of data from human respondents that are of interest. In essence, one can discern between different interview types [4]. However, since it is known in advance what information is needed, these interviews are classified as (individual basis) structured interviews. It is deliberately chosen to conduct interviews, because the data that needs to be obtained is primarily qualitative. The interviews will be held with members of the ASM team, which are responsible for the taxiway and runway maintenance strategies at Schiphol. The interviewees representing the asset management team are S. Kempen (Strategic Plan Developer), A. van der Palen (Civil Engineering Specialist) and B. Vudali (Reliability Engineer). Moreover, since Heijmans plays a prominent role in conceiving the MJOP and is also the entity that is responsible for the implementation phase, it is of essence to also incorporate the view of the contractor. To capture a complete narrative, as seen from different angles, a fourth interview will be held with H. Mooij (MJOP coordinator Heijmans).

The interviews have been structured as follows. First the interviewer introduces himself, thereafter the purpose of the interview is briefly explained and permission is asked to record the interview for transcribing purposes. An explanation of the purpose of the interview and the contributions that the interviewee can offer is pivotal, because it can motivate respondents to offer honest and fruitful answers [4]. Furthermore, confidentiality is assured to make the respondent sufficiently at ease to give informative and truthful answers.

Following the introduction of the interview, the interviewer commences with posing general questions. This is intended to establish proper trust between the interviewer and interviewee to mitigate information bias. Eventually, the interview will slowly progress into a more formal setting with questions that concern the purpose of the interview. Difficult interview questions were omitted, because when an interviewee does not understand the questions, he may feel diffident or hesitant to seek clarification. This may cause the respondent to answer the question without knowing the importance, and thus introduce bias [4]. In addition, to ensure that the respondents have no difficulties with verbalizing their perceptions, the interviews will be held in the native language, Dutch. This allows the respondents to fully articulate their perceptions. If the respondents still have difficulties with answering the questions, the questions will be rephrased.

B.2 Interview Breakdown

The interviews will commence with technical details and an introduction of both parties. This entails the following matters:

- Interviewer and respondent provide a brief introduction from both sides.
- Interviewer clarifies the purpose of the interview and how data will be processed.
- Interviewer inquires for permission to record the interview for transcribing purposes.
- Interviewer mentions that the respondent can opt for anonymity in the research.

Thereafter, the details concerning the contents will be discussed. Take notice that seven interview questions were formulated in advance and were translated to English in this section. Furthermore, some interview questions were most likely too complex or formulated too broad, which would elicit an incoherent answer. For these questions a backup question was formulated to obtain a more specific answer, if it was deemed necessary. For instance, the third interview question is very broad and different answers are valid under different circumstances. Therefore, the interview question was posed more specifically for two cases, namely the Polderbaan and taxiway Romeo. In addition, it was taken into account that important questions may arise during the conversation. To allow these questions, the number of prepared questions was kept limited to give space for improvisation opportunities. The following interview questions were formulated:

1. The MJOP is conceived by Heijmans, thereafter it will be presented to Schiphol. Subsequently, Schiphol will review the MJOP. Which processes take place after Schiphol has received the MJOP and before the definitive MJOP is determined?
2. Postponement of MJOP maintenance occurs at a regular basis, which entity within Schiphol is responsible for this decision?
3. Which factors lead to the decision to defer planned MJOP maintenance and which are paramount? (Backup question: What was the reasoning behind deferring maintenance on the Polderbaan, which was initially planned for 2018? Or maintenance on taxiway Romeo, which was deferred by four years.)
4. How does Schiphol decide which of the maintenance activities should be deferred and which activities not? How is this decision substantiated?
5. To what extent are the consequences of deferred taxiway and runway pavement maintenance considered?
6. Is the technical status of the asphalt taken into consideration and if so, to what degree and how? (e.g. pavement failures and higher maintenance costs)
7. Are there other consequences that are taken into consideration? (e.g. operational factors)

B.3 Data Processing

For processing the obtained information, recording tapes were used. Albeit that recording tapes can evoke bias in the respondents' answers during the interview [4], it was still deliberately chosen to record the interviews, if the respondent had no objection. Recordings allow the interviewer to fully focus on the interview itself and once the interview has been concluded, the interview can be easily transcribed. Consequently, information had to be derived to respond to the objective of the interviews (i.e. research question one). However, as data analysis is the most difficult and most crucial aspect of qualitative research, the interviews were coded after transcription. In this process, the transcribed narratives are tabulated, which eases the process of making sense of the textual data [98]. This coding was conducted as follows. Firstly, the transcripts were meticulously read and relevant codes were created [99]. Thereafter, trivial codes were eliminated and only a select number of codes remained. Consequently, they were either labelled as a "topic" or as a "subject" category. Thereafter, the transcribed narratives were split into smaller text fragments, as shown in Fig. B.1. Each fragment is related to codes and by ticking the boxes, it is indicated which fragments fall into which categories [99].

After the interview data was coded, attention was devoted to the primary intent of conducting the interviews. For each formulated question it was determined which codes were relevant. Consequently, when gathering the information from all the interviews to respond to a specific question, the filter functions were used to only show pertinent text fragments for that specific question. This coding structure, eases the process of finding information from a bulk of information.

Source	Sentence Number	Text Fragment	Finances	Expenses	Capacity	Supporting Documents	Airport Operations	MJOP Process	Deferring maintenance	Pavement failures	Pavement Degradation	Heijmans	ASM/Development	ASM/Asset Continuity	Operations	MJOP Projectboard	Airlines
RS1	1	**\Interviewer** What factors lead to the decision to postpone MJOP maintenance and which are paramount (e.g. finances, capacity)? **\Respondent** Those are indeed the most important reasons, together with a lack of insight of the importance and necessity of the maintenance. A thorough underpinning of the maintenance is essential. When finances and capacity are limited and the substantiation of the maintenance is insufficient, then there is the tendency to say: I can't determine the necessity, hence it is probably not that severe and we can postpone it. So again, if the severity/risks are not alarming and explicitly indicated, it is easier to defer it.	x		x	x			x					x			
RS1	2	**\Interviewer** Do you know, in advance, the budget that you will receive for the MJOP projects? **\Respondent** You know roughly what you are going to get. The MJOP is for the forthcoming five years and the consultation is every three years. Before it used to be on annual basis. So, we have consulted with the airlines for the upcoming three years, hence we know what the budgets are. We also know what Heijmans has put in the MJOP for year four and five, therefore we already have a rough estimation. Since the large projects conducted by Heijmans are maintenance on the runways or taxiways, we know, from past experience, approximately the costs of replacing a TDZ or a runway.	x	x													x

Fig. B.1. Interview Coding Approach.

B.4 Interview Transcripts

Due to the sheer size of the interview transcriptions, they were deliberately kept separate from this research. One may request a separate booklet of the interview transcripts by contacting the author of this research.

Appendix C

Examples of Pavement Failures

(a) Pothole in Taxiway A8 Behind VOP F08.

(b) Corrugation in Taxiway A16.

(c) Pothole in Taxiway behind VOP G06.

(d) Pothole in Taxiway A10 behind VOP D47.

(e) Pothole next to the Centerline in Taxiway A04.

(f) Damage at Head of Runway 18L.

Fig. C.1. Examples of Reported Pavement Failure.

Appendix D

Point Density Heatmap of Schiphol

Fig. D.1. Heatmap of Data Point Density.

Appendix E

Origin-Destination Matrices

O/D matrix		Destination: Bays A	B	BC	CD	D	DE	EF	FG	G	H	R	S	Σ
Origin: Buitenveldertbaan	N1	0	0	0	0	0	0	0	0	0	0	0	0	0
	N2	390	258	462	482	215	353	118	146	86	255	37	69	2870
	N3	1755	1161	2077	2168	968	1587	529	658	387	1148	168	310	12915
	N4	641	424	758	791	353	579	193	240	141	419	61	113	4715
	N5	0	0	0	0	0	0	0	0	0	0	0	0	0
Zwanenburgbaan	W1	0	0	0	0	0	0	0	0	0	0	0	0	0
	W2	223	148	264	276	123	202	67	84	49	146	21	39	1644
	W3	1192	789	1411	1472	657	1078	359	447	263	780	114	210	8770
	W4	447	296	529	552	247	404	135	168	99	293	43	79	3290
	W6	1252	829	1482	1547	690	1132	377	469	276	819	120	221	9215
	W7	3339	2210	3953	4125	1841	3020	1007	1252	737	2185	319	589	24576
	W8	626	414	741	773	345	566	189	235	138	410	60	110	4608
	W9	0	0	0	0	0	0	0	0	0	0	0	0	0
	W10	0	0	0	0	0	0	0	0	0	0	0	0	0
Aalsmeerbaan	E1	1077	713	1275	1330	594	974	325	404	238	705	103	190	7925
	E2	3015	1995	3569	3724	1663	2727	909	1131	665	1973	288	532	22190
	E4	43	29	51	53	24	39	13	16	10	28	4	8	317
	E5	172	114	204	213	95	156	52	65	38	113	16	30	1268
	E6	0	0	0	0	0	0	0	0	0	0	0	0	0
Polderbaan	V1	2787	1845	3300	3443	1537	2521	840	1045	615	1824	266	492	20516
	V2	6060	4010	7173	7485	3342	5480	1827	2272	1337	3965	579	1069	44600
	V3	3272	2165	3874	4042	1804	2959	986	1227	722	2141	313	577	24084
	V4	0	0	0	0	0	0	0	0	0	0	0	0	0
Oostbaan	G4	18	12	22	23	10	17	6	7	4	12	2	3	135
	G5	348	231	413	430	192	315	105	131	77	228	33	61	2566
Kaagbaan	S3	1682	1113	1991	2078	928	1521	507	631	371	1101	161	297	12380
	S4	4487	2969	5312	5542	2474	4058	1353	1683	990	2936	429	792	33024
	S5	0	0	0	0	0	0	0	0	0	0	0	0	0
	S6	841	557	996	1039	464	761	254	315	186	551	80	148	6192
	S7	0	0	0	0	0	0	0	0	0	0	0	0	0
Σ		33667	22280	39856	41589	18566	30449	10150	12625	7427	22032	3218	5941	247800

(a) Origin-Destination Matrix for Arriving Traffic.

D/O matrix		Origin: Bays A	B	BC	CD	D	DE	EF	FG	G	H	R	S	Σ
Destination: Buitenveldertbaan	N1	136	90	161	168	75	123	41	51	30	89	13	24	1000
	N2	0	0	0	0	0	0	0	0	0	0	0	0	0
	N3	0	0	0	0	0	0	0	0	0	0	0	0	0
	N4	173	115	205	214	96	157	52	65	38	113	17	31	1275
	N5	986	652	1167	1218	544	891	297	370	217	645	94	174	7255
Zwanenburgbaan	W1	126	83	149	155	69	114	38	47	28	82	12	22	924
	W2	15	10	18	19	8	14	5	6	3	10	1	3	112
	W3	31	20	36	38	17	28	9	12	7	20	3	5	226
	W4	13	9	16	16	7	12	4	5	3	9	1	2	98
	W6	0	0	0	0	0	0	0	0	0	0	0	0	0
	W7	0	0	0	0	0	0	0	0	0	0	0	0	0
	W8	101	67	119	124	56	91	30	38	22	66	10	18	741
	W9	268	178	318	332	148	243	81	101	59	176	26	47	1976
	W10	2987	1976	3536	3689	1647	2701	900	1120	659	1955	285	527	21983
Aalsmeerbaan	E1	0	0	0	0	0	0	0	0	0	0	0	0	0
	E2	0	0	0	0	0	0	0	0	0	0	0	0	0
	E4	473	313	560	584	261	428	143	177	104	309	45	83	3480
	E5	1970	1304	2332	2434	1086	1782	594	739	435	1289	188	348	14500
	E6	5437	3598	6437	6717	2999	4918	1639	2039	1199	3558	520	960	40020
Polderbaan	V1	0	0	0	0	0	0	0	0	0	0	0	0	0
	V2	0	0	0	0	0	0	0	0	0	0	0	0	0
	V3	1705	1128	2018	2106	940	1542	514	639	376	1115	163	301	12546
	V4	7765	5139	9193	9592	4282	7023	2341	2912	1713	5082	742	1370	57154
Oostbaan	G4	0	0	0	0	0	0	0	0	0	0	0	0	0
	G5	0	0	0	0	0	0	0	0	0	0	0	0	0
Kaagbaan	S3	0	0	0	0	0	0	0	0	0	0	0	0	0
	S4	0	0	0	0	0	0	0	0	0	0	0	0	0
	S5	4641	3071	5494	5733	2559	4197	1399	1740	1024	3037	444	819	34160
	S6	2901	1920	3434	3583	1600	2623	874	1088	640	1898	277	512	21350
	S7	3481	2303	4121	4300	1920	3148	1049	1305	768	2278	333	614	25620
Σ		33208	21976	39312	41022	18313	30034	10011	12453	7325	21732	3174	5860	244420

(b) Origin-Destination Matrix for Departing Traffic.

Fig. E.1. Origin-Destination Matrix for Schiphol.

Appendix F

Cox PH Model SPSS Output

Block 1: Method = Enter

Omnibus Tests of Model Coefficients[a]

-2 Log Likelihood	Overall (score) Chi-square	df	Sig.	Change From Previous Step Chi-square	df	Sig.	Change From Previous Block Chi-square	df	Sig.
3977.945	80.358	8	.000	85.740	8	.000	85.740	8	.000

a. Beginning Block Number 1. Method = Enter

(a) Omnibus Test.

Covariate Means

	Mean
Pavement_Category(1)	.341
Pavement_Category(2)	.073
Pavement_Category(3)	.160
Pavement_Category(4)	.224
Aircraft_Speed	8.557
Stationary_Category	2.222
LN_Movements	10.625
Surface_Deflection	258.936

(b) Covariate Means.

Variables in the Equation

	B	SE	Wald	df	Sig.	Exp(B)	95.0% CI for Exp(B) Lower	Upper
Pavement_Category			20.548	4	.000			
Pavement_Category(1)	.039	.243	.025	1	.004	1.039	.646	1.672
Pavement_Category(2)	-.264	.244	1.176	1	.078	.768	.476	1.238
Pavement_Category(3)	-.132	.176	.569	1	.051	.876	.621	1.236
Pavement_Category(4)	-.711	.216	10.814	1	.001	.491	.322	.750
Aircraft_Speed	-.039	.017	5.521	1	.019	.962	.931	.994
Stationary_Category	.158	.057	7.587	1	.006	1.171	1.047	1.310
LN_Movements	.238	.068	12.306	1	.000	1.269	1.111	1.449
Surface_Deflection	.000	.000	3.120	1	.077	1.000	1.000	1.001

(c) Variables Coefficients, Significance and Confidence Intervals.

Fig. F.1. SPSS Cox PH model Results.

Appendix G

Dynamic Choropleth In- and Output

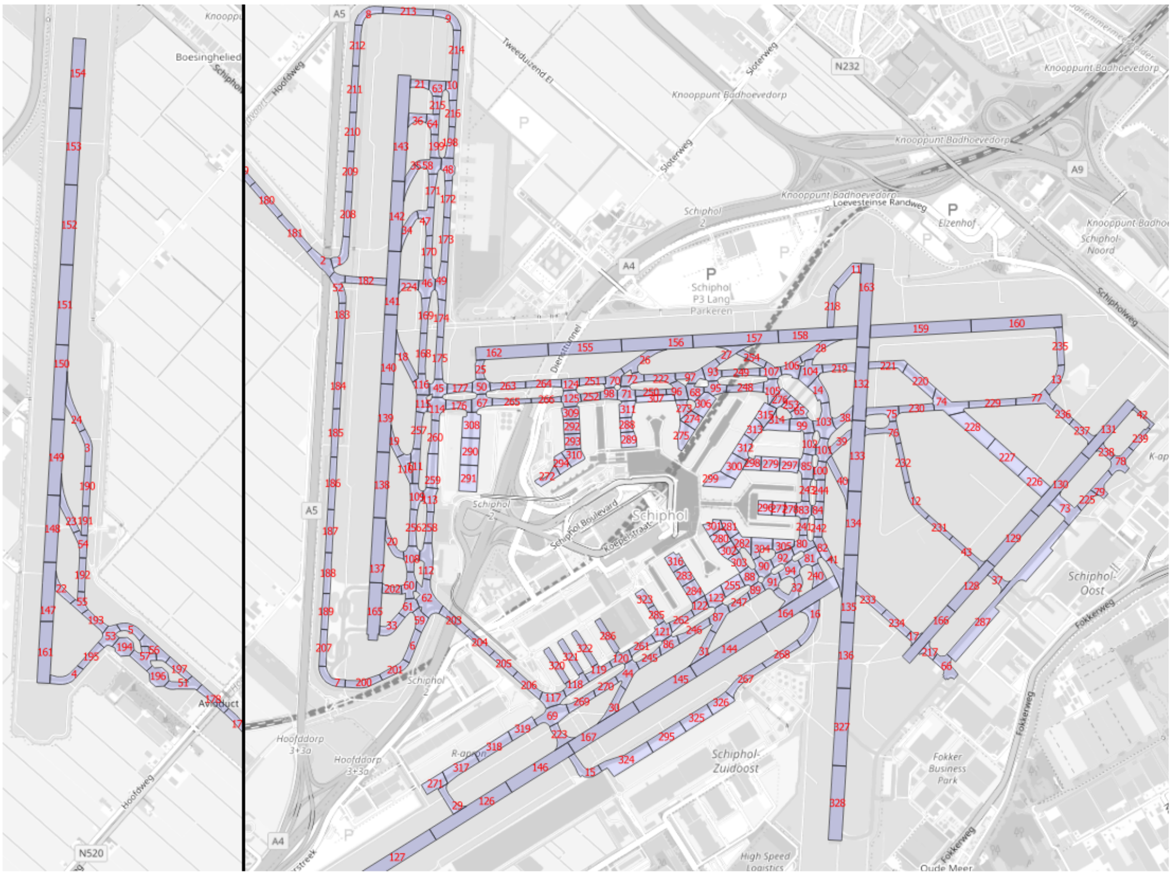


Fig. G.1. Pavement Grid ID's.

Fig. G.2. Choropleth Model Part 2018.

Fig. G.3. Choropleth Model 2019.

Fig. G.4. Choropleth Model 2020.

Fig. G.5. Choropleth Model 2021.

Fig. G.6. Choropleth Model 2022.

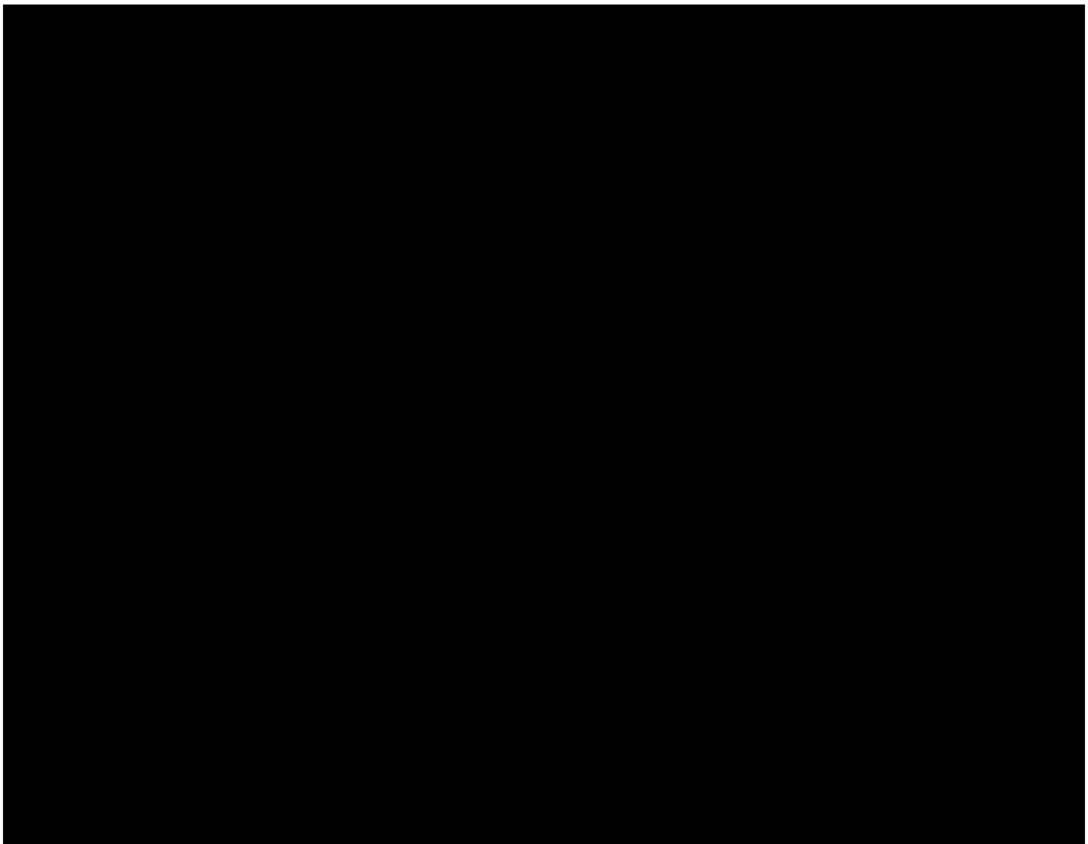
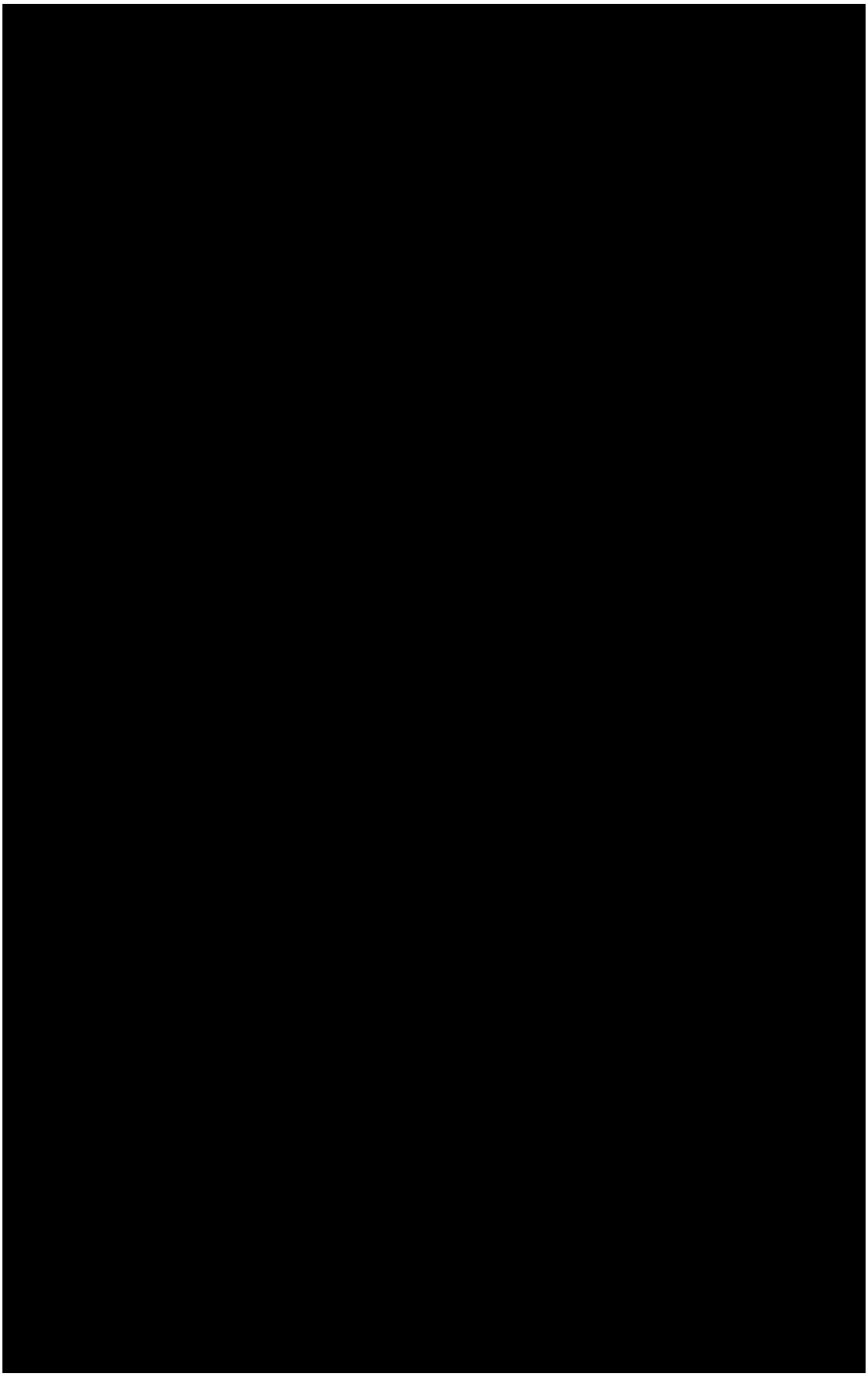
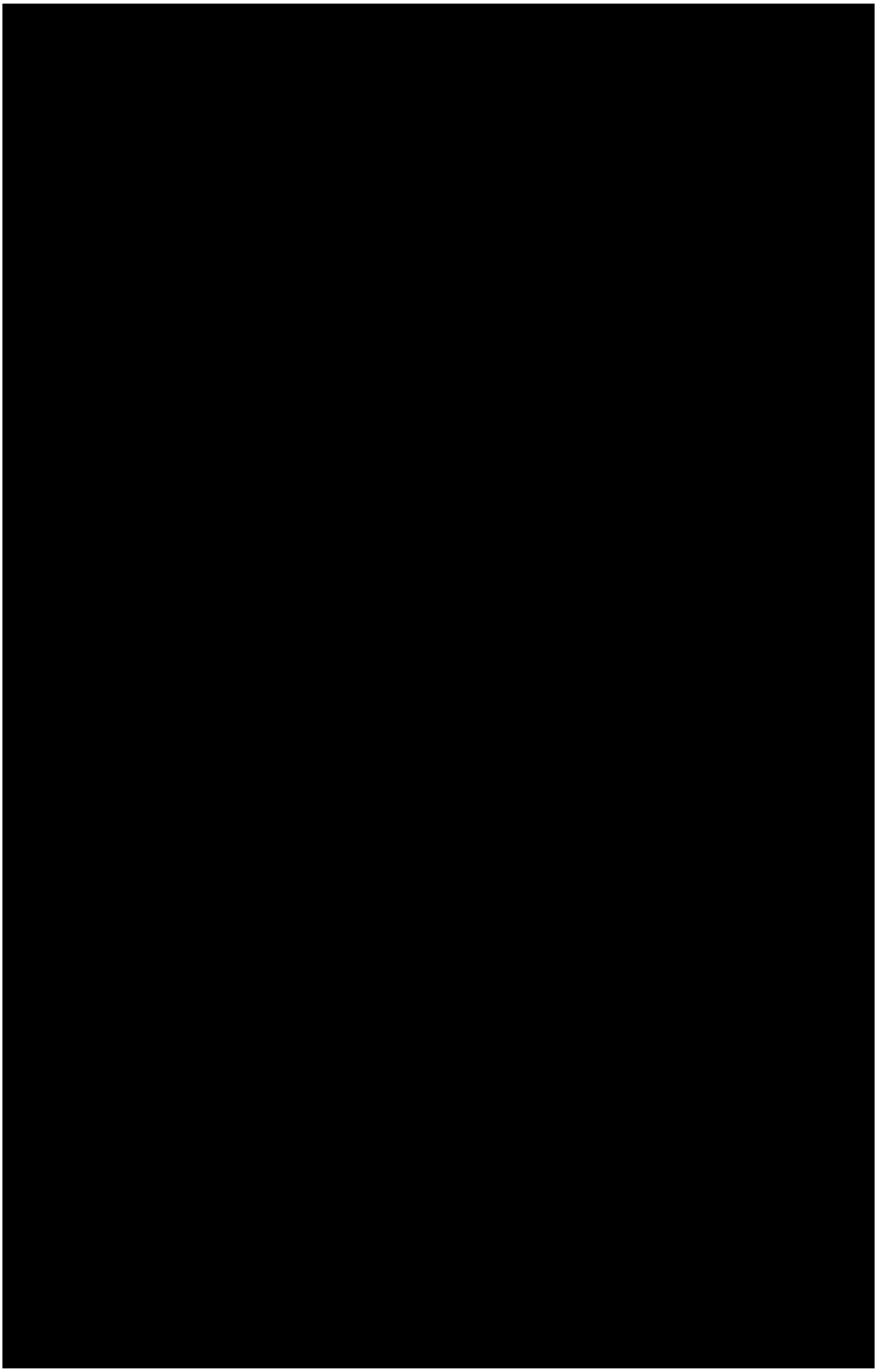
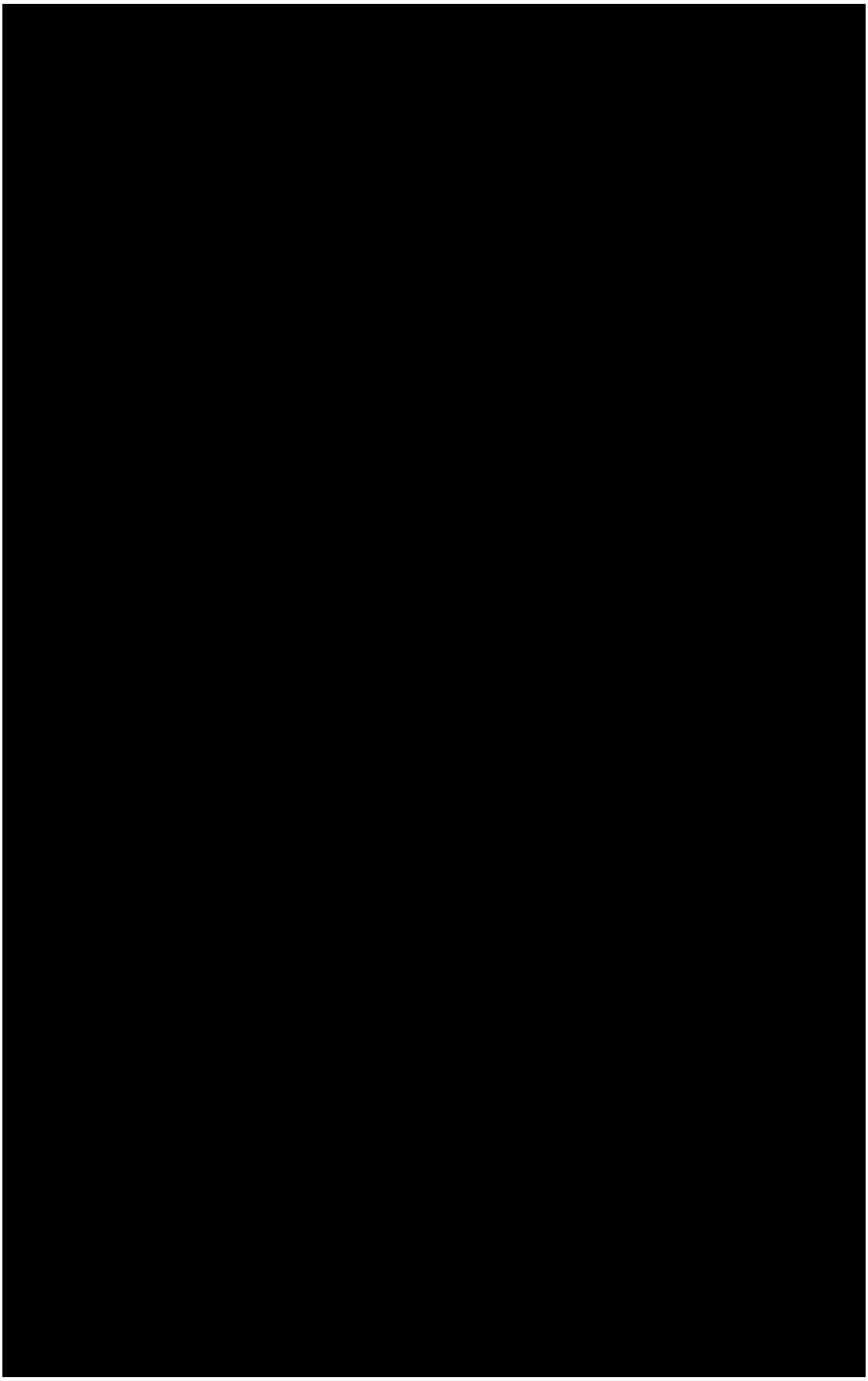
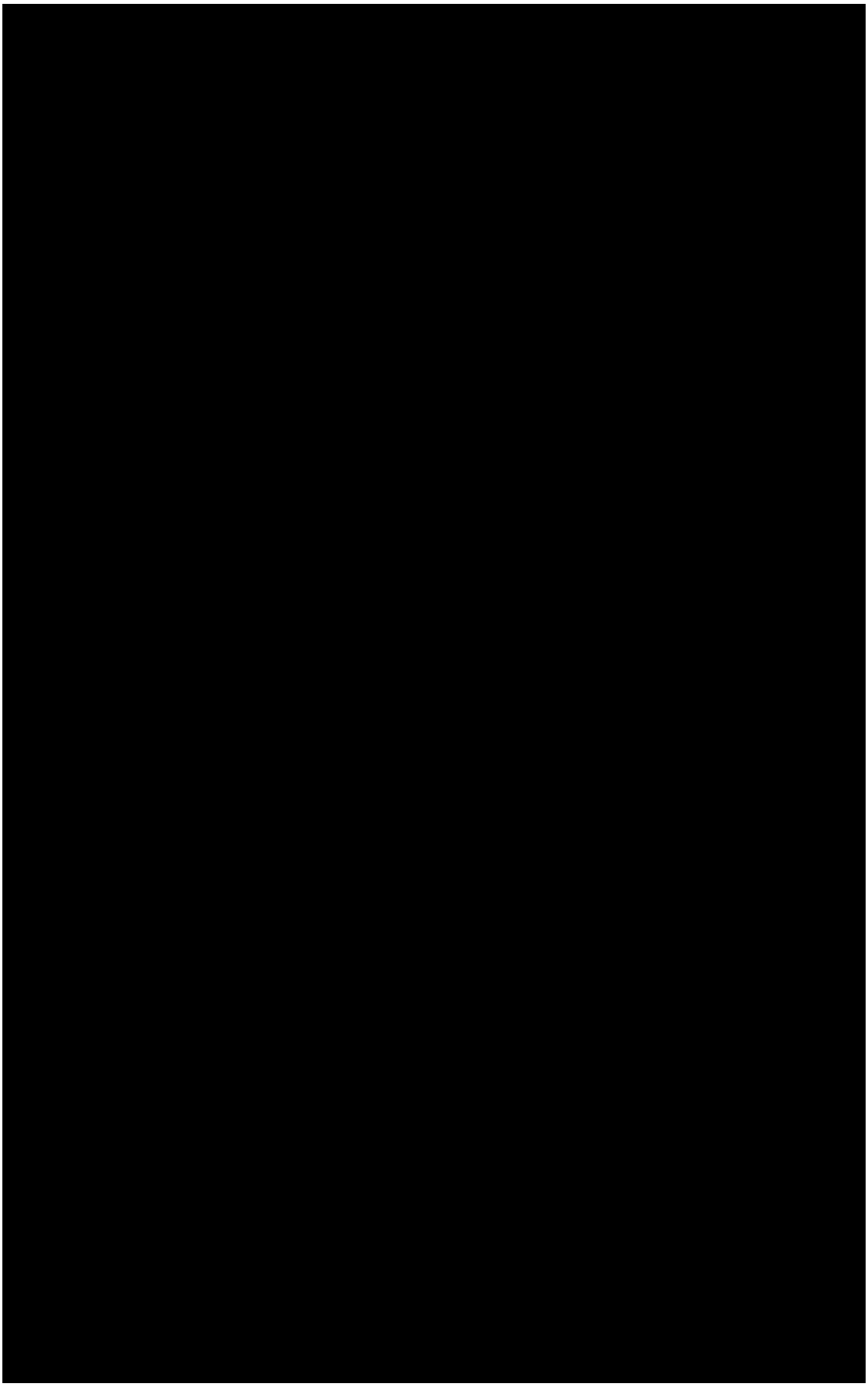


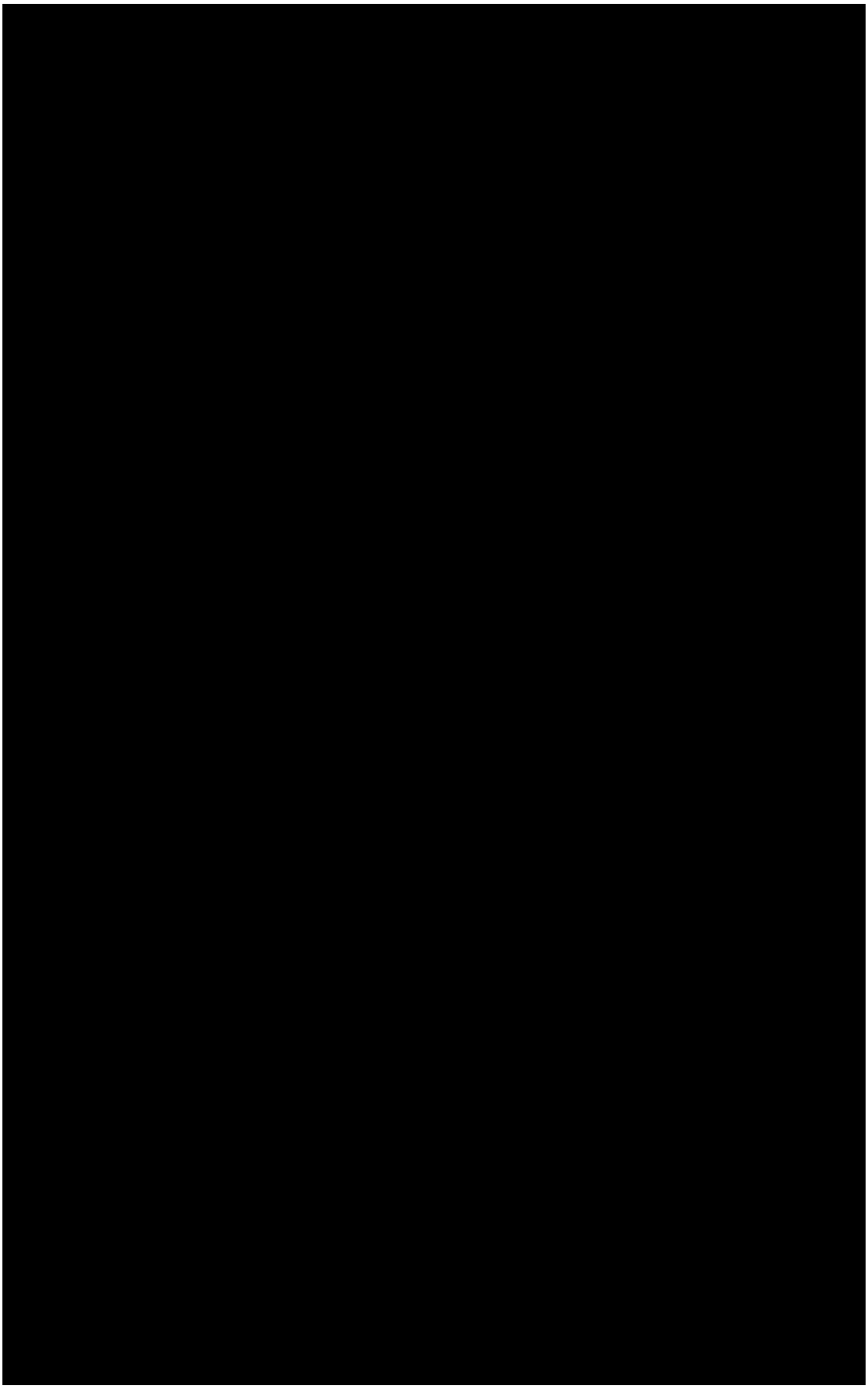
Fig. G.7. Choropleth Model 2023.











[redacted]

Appendix H

Risk Matrix

Likelihood	Potential Consequence				
	Negligible	Minor	Moderate	Major	Extreme
Almost Certain	Medium	High	High	Very high	Very high
Likely	Medium	Medium	High	High	Very high
Possible	Low	Medium	Medium	High	High
Unlikely	Low	Medium	Medium	Medium	High
Rare	Low	Low	Low	Medium	Medium

Fig. H.1. Risk Matrix adopted from M. Tannahill [94].