Improving Airport Taxiway Systems

Exploring challenges and opportunities based on the Amsterdam Airport Schiphol case

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TU Delft

NACO
a company of Royal HaskoningDHV

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Exploring challenges and opportunities based on the Amsterdam Airport Schiphol case

in partial fulfilment of the requirements for the degree of

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PREFACE

With Maastricht Aachen Airport around the corner in my home village, my interest in aviation emerged quickly. After high school, I decided to leave Limburg and move to Delft to study Civil Engineering with the minor 'Airport of the Future'. At the end of this Bachelor program, I got the opportunity of joining the Airport Civil Engineering team of Netherlands Airports Consultants (NACO) for an internship, in which I learned a lot on many aspects of airport design. Subsequently, I continued studying at the Delft University of Technology by attending the Master of Science in Transport, Infrastructure and Logistics, with plenty of opportunities for aviation-related courses and topics. This report is the result of the master thesis research, which I conducted as my final assessment of the study program.

During the entire research I have had a great support from people around me. Therefore I would like to give a special word of thanks to the following people:

Firstly, a word of thanks to all interviewees for their time and sharing their knowledge and experiences within the aviation industry. Their contributions were of great added value to the research.

Secondly, I would like to thank my thesis committee within the TU Delft. Starting with John Baggen; coincidentally, we met during a train-ride, during which we discussed my thesis topic for the first time. I am grateful for his supervision and keeping me heading for the end goals. My gratitude also goes to John Stoop for giving input based on his broad experience in (aviation) safety. His frank opinion and thoughts helped me gaining broader insights. I also would like to thank Paul Roling for (again) sharing his extensive knowledge on the aviation industry, as well as Serge Hoogendoorn for his willingness to chair my thesis committee and sharing his enthusiasm and knowledge.

Thirdly, I am thankful to Jelmer van der Meer, for providing me the opportunity to graduate on this topic and join the Airport Civil Engineering team of NACO once more, as well as to my other colleagues at NACO for expressing their interest in the thesis and making me feel welcome. They were always willing to help. Off course, a special word of thanks to Peter Vorage as my supervisor at NACO. His critical mind really motivated me to get the best out of my thesis research.

Finally, I am grateful for the support of my family and friends, who continuously motivated me and showed their interest in the work I was performing. In special, I would like to thank Kevin for his love, but also for his practical way of thinking and point of view, which were very helpful the times I got stuck. Last but not least, a word of thanks to Stefan, Rick, William and Martijn; my fellow students who became true friends. Helping each other during our graduation period has been a pleasure and very valuable.

Hopefully, you enjoy reading this report and also become enthusiastic about the aviation industry and airports in specific.

Remco Troquete
Delft, April 2020

P.S. The cover picture of this thesis shows KLM's first Boeing 787-10 Dreamliner (60m wingspan) arriving at AAS, taxiing over a taxiway (normally) limited to aircraft with a wingspan of 36 meters to take a promotional picture. Thus, the in this report described deviations from standard procedures are sometimes made intentionally for promotional purposes and/or pleasure.

ABSTRACT

The almost ceaselessly growing Air Transportation System (ATS) has led to concerns across airports on how to deal with this growth. Also Amsterdam Airport Schiphol (AAS) experienced large increases in number of passengers and movements over the last decades: the current limit of 500,000 annual movements of the airport is (nearly) reached. Before stretching the current limit, AAS shall demonstrate that its growth is safely possible. In the past, both Hillestad et al. (1993) and the Dutch Safety Board (2017) investigated the safety at AAS and concluded that, despite vulnerabilities, the airport was safe.

This research explores challenges and opportunities towards improving airport taxiway systems. Therefore, a currently lacking definition for taxiway system at systems level is defined first. Besides, Key Performance Indicators (KPIs) for taxiway systems are defined in order to identify parameters for improving the system based on stakeholders' point of views: safety, capacity, robustness, and environmental impact. Also methods for assessing taxiway systems on these identified KPIs are defined. Next, AAS is used as a case study to analyze the performance of the taxiway system at the airport on the defined safety KPI. As part of the safety analysis of AAS, for the first time a taxiway system was analyzed on the sustainable safety vision as developed for road traffic - and showed to be valuable. Based on the safety analysis, challenges and opportunities within the taxiway system are identified and recommendations provided.

On the operational safety of the taxiway system at AAS, the following is concluded. The present taxiway system seems to be safe, yet shows challenges and opportunities for improvements. Looking at the legacy of AAS, Dellaert's 1950s master plan showed to deliver a solid airport system. The design, based on 2 million passengers and 100,000 movements in the 1970s/1980s, appeared to be able to handle 71.7 million passengers and almost 500,000 movements last year with extended terminal areas and piers in the by Dellaert designated central traffic area and one additional runway. Nonetheless, pressure from Air Traffic Control (ATC) on flight crews seems to increase and deviating from standards and procedures by both ATC and flight crews seems normalized. Moreover, due to a lacking strict definition of through taxi-routes, it appears that the 'greyness' of the definition of apron taxiways is utilized in the taxiway design in order to handle the peak traffic demands within the set systems boundaries. Hence, the present taxiway system tends to reach its safe operational limits, suggesting the system reached the 'wear-out' phase of the bathtub curve. This might partly be the result of 'practical drift' throughout the years.

Despite the steps the aviation industry in The Netherlands has made towards an integral approach on safety, care must be taken to ensure that the taxiway system is not underexposed and that safety continuously remains a first considerations and is not unnecessarily or unconsciously subordinated.

Keywords: Taxiway System, Airport Surface Safety, Sustainable Safety, Amsterdam Airport Schiphol

SAMENVATTING

De afgelopen jaren heeft de wereldwijde luchtvaartsector een bijna onafgebroken groei doorgemaakt. Dat heeft geleid tot zorgen onder luchthavens over hoe ze met die groei om moeten gaan. Ook Amsterdam Airport Schiphol (AAS) heeft de laatste decennia een grote groei doorgemaakt, waardoor de huidige jaarlijkse limiet van 500.000 vliegtuigbewegingen (bijna) is bereikt. De Nederlandse overheid heeft voor verdere groei van AAS de voorwaarde gesteld dat dit op een aantoonbaar veilige manier mogelijk moet zijn. In het verleden hebben zowel RAND Europe (Hillestad et al., 1993) en de Onderzoeksraad voor Veiligheid (Dutch Safety Board, 2017) de veiligheid van AAS onderzocht. Zij beoordeelden de luchthaven, ondanks verbeterpunten, als veilig.

In dit onderzoek worden uitdagingen en mogelijkheden voor het verbeteren van taxibaansystemen op luchthavens verkend. Om dit te doen is er eerst een momenteel ontbrekende definitie voor taxibaansystemen op systeemniveau gedefinieerd. Daarnaast zijn er op basis van opvattingen van belanghebbenden en gebruikers vier Key Performance Indicators (KPIs) voor taxibaansystemen gedefinieerd: veiligheid, capaciteit, robuustheid en milieu impact. Ook zijn er methoden om deze KPIs te meten en beoordelen opgesteld. Vervolgens is AAS gebruikt als casus om the prestaties van het taxibaansysteem op de luchthaven te analyseren aan de gedefinieerde veiligheid KPI. Als onderdeel van deze veiligheidsanalyse is er voor het eerst gebruik gemaakt van de Duurzaam Veiligheid visie, welke ontwikkeld en bewezen waardevol is voor wegverkeer.

Uiteindelijk is er geconcludeerd dat het huidige taxibaansysteem op AAS veilig is, maar ook uitdagingen en mogelijkheden voor verbeteringen laat zien. Het in de jaren 1950 opgestelde master plan voor AAS van Jan Dellaert, de eerste havenmeester van AAS, bleek te zorgen voor een degelijk luchthavensysteem. Het ontwerp, dat gebaseerd was op 2 miljoen passagiers en 100.000 vliegtuigbewegingen in de jaren 1970/1980, bleek in staat te zijn om in 2019 71.7 miljoen passagiers en bijna 500.000 vliegtuigbewegingen af te kunnen handelen. Hiervoor is slechts één start-/landingsbaan toegevoegd, en is in het door Dellaert aangewezen terminalgebied het aantal pieren uitgebreid. Desalniettemin lijkt de druk van de luchtverkeersleiding (ATC) op piloten toe te nemen. Daarnaast lijkt het afwijken van standaarden en procedures door zowel luchtverkeersleiding als piloten genormaliseerd te zijn. Het huidige taxibaansysteem lijkt dan ook zijn veilige operationele grenzen te hebben bereikt, wat erop duidt dat het systeem de zogenoemde eindperiode van de badkuipkromme heeft bereikt. Bovendien mist er in ICAO's Annex 14 een eenduidige definitie van doorgaande taxi-routes, waardoor de 'grijsheid' van de definitie van apron taxiways gebruikt wordt om piekverkeer af te handelen binnen de systeemgrenzen. Mogelijk is dit deels het gevolg van 'practical drift' door de jaren heen: het ontwerp is gemaakt in een theoretisch kader, maar het daadwerkelijke gebruik is vaak anders en drijft dus weg van aangenomen uitgangspunten.

Ondanks de stappen die de luchtvaartindustrie in Nederland heeft gemaakt voor een integrale aanpak van veiligheid, is het belangrijk dat het taxibaansysteem niet onderbelicht wordt. Daarnaast moet ervoor worden gewaakt dat veiligheid de topprioriteit blijft en niet onnodig of onbewust ondergeschikt wordt gemaakt.

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ACRONYMS

AAS	Amsterdam Airport Schiphol
A-CDM	Airport Collaborative Decision Making
ACI	Airport Council International
ASMGCS	Advanced Surface Movement Guidance and Control System
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Transportation System
BARIN	Board of Airlines Representatives In the Netherlands
CDM	Collaborative Decision Making
CFMU	Central Flow Management Unit
CPDSP	Collaborative Pre-Departure Sequence Planning
CTOT	Calculated Take Off Time
DAAD	Deviation Acceptance and Action Document
DIWT	De-Icing Waiting Time
EASA	European Union Aviation Safety Agency
EDIT	Estimated De-Icing Time
ELoS	Equivalent Level of Safety
EXOT	Estimated Taxi-Out Time
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FOD	Foreign Object Debris
GA	General Aviation
GAE	Groningen Airport Eelde
GPU	Ground Power Unit
GTS	Gezamenlijke Tankdiensten Schiphol (*Joined Fueling Services Schiphol*)
IAF	Initial Approach Fix
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IDM	Integral Design and Management
IFR	Instrument Flight Rules
ILT	Inspectie Leefomgeving & Transport (*Human Environment and Transport Inspectorate*)
ISMS	Integral Safety Management System
KLM	Royal Dutch Airlines
KPI	Key Performance Indicator
LVNL	Air Traffic Control the Netherlands
LVP	Low Visibility Procedures
LTO	Landing and takeoff cycle
MAA	Maastricht Aachen Airport
NaBo	Narrow Body aircraft
NACO	Netherlands Airports Consultants
OMGWS	Outer Main Gear Wheel Span
ORS	Omgevingsraad Schiphol (*Environmental Council Schiphol*)
PHI	Potentially Hazardous Interaction
RET	Rapid Exit Taxiway

RPK	Revenue Passenger Kilometers
RVR	Runway Visual Range
SARPs	Standards and Recommended Practices
SC	Special Condition
SE	Systems Engineering
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure route
SQ	Sub Question
TOBT	Target Off-Block Time
TSAT	Target Start-up Approval Time
TTOT	Target Take Off Time
UML	Unified Modeling Language
VDGS	Visual Docking Guidance System
VNV	Vereniging Nederlandse Verkeersvliegers (*Dutch Airline Pilots Association*)
VFR	Visual Flight Rules
WiBo	Wide Body aircraft
WTC	Wake Turbulence Category

1 INTRODUCTION

For the last decades, the Air Transportation System (ATS) has been growing almost ceaselessly: IATA (2019) globally measured an average yearly growth of 5.5% in Revenue Passenger Kilometers (RPK). The International Air Transport Association (IATA) expects this growth to continue; they forecast a growth from 4 billion passengers in 2016 to 7.8 billion passengers in 2036 (IATA, 2017). Consequently, the ATS should either grow or be improved to facilitate the expected growth.

The described growth in the ATS can also be found at Amsterdam Airport Schiphol (AAS), where the number of passengers has grown from 19 million passengers in 1992 up to 71.7 million passengers in 2019 (Royal Schiphol Group, 2019b). Accordingly, also the number of aircraft movements increased: from 239,000 (1992) to 496,826 (2019). [1] Hence, the current limit of 500,000 movements per year[2] at AAS is (nearly) reached.

This chapter provides an introduction to this master thesis. First, Section 1.1 introduces safety concerns within the ATS at AAS due to the past and potential growth. Second, Section 1.2 provides a decomposition of the ATS resulting in the topic of this research: taxiway systems, and the used case study: AAS. Third, Section 1.3 provides the problem statement for the research. Fourth, Section 1.4 defines the research objective and scope. Fifth, Section 1.5 presents the Research Question and corresponding Sub Questions. Sixth, in Section 1.6 the approach to the research is elaborated. Finally, in Section 1.7, the outline of this thesis report is presented.

1.1 SAFETY CONCERNS AMSTERDAM AIRPORT SCHIPHOL

The Dutch Minister of Infrastructure and Water Management (2019a) underpinned the economical importance of AAS as major airport in The Netherlands, offering connectivity to the world. Yet, the Minister stated that she will only allow AAS to grow further after 2020 providing that a set of defined criteria are met (2019a):

- Environment: The emission of CO_2 shall be reduced;
- Nuisance: The nuisance for AAS's neighbours shall be reduced, especially during night-hour operations;
- Quality: Growth shall be used as much as possible to support the network quality of AAS;
- Safety: growth will only be allowed if this is demonstrable safely possible.

The final criterion (safety) as defined by the Dutch Minister might cause major challenges.

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[1] Definition **Aircraft Movement**: *"An aircraft takeoff or landing at an airport. For airport traffic purposes one arrival and one departure is counted as two movements."* (ICAO, 2013b)

[2] Until 2021, the growth of AAS is limited to a number of 500,000 annual aircraft movements (one movement means one takeoff or one landing). This number includes commercial air traffic (referred to as '**handelsverkeer**') and does not include general aviation and technical air traffic (Government of The Netherlands, 2019; Schiphol, 2018d).

Back in the 1990's, when expansion of AAS was contemplated too, concerns about safety risks increased. Those concerns raised to a peak by the crash of a freight carrier into an apartment complex in the Bijlmermeer in October 1992. Consequently, Hillestad et al. (1993) examined the (external) safety at AAS in a time the airport was about to evolve from airport to mainport and in time of liberalization of the ATS. Based on their research, Hillestad et al. (1993) found AAS to be a safe airport in comparison to other airports in Europe and the United States. Nevertheless, the proposed evolution entailed growth, which could lead to a potentially increased risk for third parties. Yet, Hillestad et al. (1993) expected that external risk could be kept limited by mitigating factors such as adaption of technological improvements, both in aircraft and airport systems. In general, the researchers expected a continuous tension between the economic importance of expansion, the environmental effects and safety. However, Hillestad et al. (1993) recommended that management should set "safety first" as a goal of all organizations associated with AAS.

More recently, the Dutch Safety Board (2017) concluded that the past growth had an adverse effect on the safety of airside operations at AAS. This conclusion was drawn in a research report in response to a series of incidents at the airport. For the report, the board investigated vulnerabilities at AAS concerning the safety of airside operations. The report exposes several safety risks, which should be tackled to ensure safe operations in the future. Frequent changes in runway configuration, which are the result of environmental and economical considerations (i.e. noise nuisance, arrival and departure peaks), result in a complex traffic handling process. Consequently, Air Traffic Controllers (ATCOs) operate under high workloads. Additionally, the large number of taxiways, runway exits and entries (including Rapid Exit Taxiways (RETs)) and relative runway orientations rise the safety risk (Dutch Safety Board, 2017). Moreover, the board concluded that confusion of the pilots (flight crew) and runway incursions (further investigated by Koopmans (2019) in his master thesis) might be caused by the large number of taxiways and the use of RETs for entering the runway. One of the recommendations in the report is reducing the complexity of the airside infrastructure (including taxiways) at the airport.

Despite Hillestad et al. (1993) and the Dutch Safety Board (2017) concluding that AAS is safe, both also exposed vulnerabilities concerning the safety of airside operations to be tackled before safe growth is possible.

1.2 THE AIRPORT TAXIWAY SYSTEM

As mentioned, the almost ceaselessly growth of the ATS has led to an increase of safety risks in operations at airports like AAS, impacting the airport's subsystems as well. Moreover, the growth is forecast to continue in the future (IATA, 2017). This leads to increasing concerns amongst airports on how to deal with the growing traffic volumes (Eurocontrol, 2019). Since growing is a high costly and time consuming process for airport systems (de Neufville and Odoni, 2013), the first step in dealing with the forecast growth is improving the airport system's subsystems. In order to further understand the ATS, first understanding of a system is provided. In his book, Wasson (2015) stated a definition for a system:

> "*An integrated set of inter-operable elements or entities, each with specified and bounded capabilities, configured in various combinations that enable specific behaviors ... in a prescribed operating environment with a probability of success*". (Wasson, 2015, p. 792)

The provided definition can also be used to describe the ATS. Hence, Systems Engineering (SE) is used for defining and structuring the various elements of the ATS throughout this thesis. The "V-model", which was originally introduced by Forsberg and Mooz (1991), is used by Schmitt and Gollnick (2016) to describe how new solutions for the ATS can be developed (Figure 1.1). The V-model allows for decomposition of the system in small parts and provides a highly iterative approach for improvement of each design step in order to identify, quantify and minimize risks (Forsberg and Mooz, 1991).

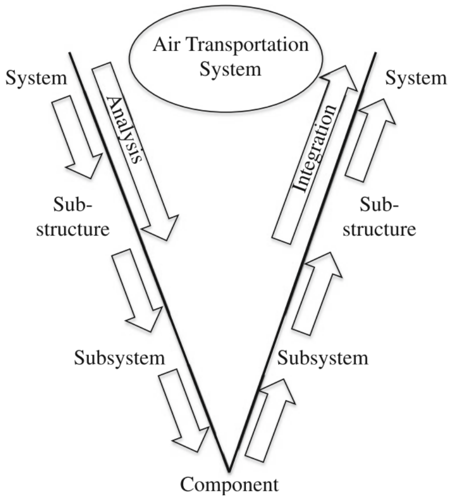


Figure 1.1: V-model of the Air Transportation System (Schmitt and Gollnick, 2016)

Schmitt and Gollnick (2016) defined four system-levels for the ATS. To facilitate the growing ATS, also the system's Sub-Structures will have to grow, either in size or in number, or have to be optimized. Hence, also the subsystems and its components will have to deal with a growing system. In Figure 1.2 a breakdown of the ATS on the upper three system levels of the ATS as described by Schmitt and Gollnick (2016) focusing on the Airport sub-structure is provided.

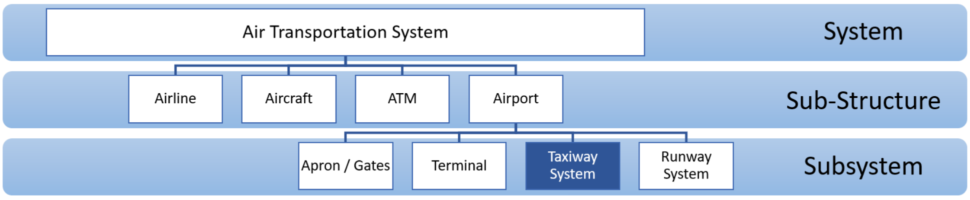


Figure 1.2: Air Transportation System Breakdown up to subsystem-level, based on Oostra (2019) and Schmitt and Gollnick (2016)

As can be seen in Figure 1.2, the ATS's sub-structure 'Airport' is build up of four subsystems, including the runway system and taxiway system. On the runway system, several studies have been performed (e.g. Koopmans, 2019). Yet, amongst others, an example of a takeoff from a taxiway at AAS (Dutch Safety Board, 2011) emphasizes safety risks within the taxiway system as well.

For the airport sub-structure focusing on surface infrastructure, including the taxiway system, Wilke et al. (2014) identified three major actors: Pilots (operating the aircraft), Air Traffic Control (ATC), guiding pilots over the surface and other vehicles and pedestrians, which primarily can be found on the aprons by means of ground handlers. Besides, airport operators are important actors, as well as regulators. Moreover, the environment and other external stakeholders are considered by Wilke et al. (2014) as actors within the airport system.

1.3 PROBLEM STATEMENT

In order to facilitate the growing ATS without expensive and time consuming expansions of airports, improving its subsystems is considered the first step. The taxiway system is one of the airport's subsystems that should be improved. Therefore, this master thesis focuses on exploring opportunities and remaining challenges for improving airport taxiway systems, with a focus on safety. However, a taxiway system definition at systems level is lacking in the literature. Besides, an overview of taxiway systems' Key Performance Indicators (KPIs) based on stakeholders' point of views, and how to measure and assess them is lacking. These are needed to place safety in perspective within the system.

Given the forecast growth of AAS, the conditions the Minister set for this and the issues regarding safety on the airport as pointed out by both Hillestad et al. (1993) and the Dutch Safety Board (2017), AAS is considered to be a good case for this study for finding opportunities and remaining challenges for improvements in the taxiway system.

1.4 RESEARCH OBJECTIVE AND SCOPE

The objective of this research is to explore challenges and opportunities towards improving airport taxiway systems. Therefore, first, a currently lacking definition for taxiway system at systems level will be defined. Besides, KPIs for taxiway systems are defined in order to identify parameters for improving the system based on stakeholders' point of views. Also methods for assessing taxiway systems on these identified KPIs will be defined. Next, AAS is used as a case study to analyze the performance of the taxiway system at the airport on the defined safety KPI. Based on this analysis, challenges and opportunities within the taxiway system can be identified. For these challenges and opportunities, recommendations for improving taxiway systems at airports will be provided.

To limit the scope of the research, only airports within Europe are considered. In Section 3.1, more details on global differences are provided. From this section, it can be concluded that both on design as well as on operational usage there are clear differences between Europe and other continents. Since the inducement of the study is AAS, the geographical scope will be European airports. Besides, considered airports should meet the following general requirements:

- Presence of commercial air traffic;
- Presence of ATC at the airport (towered airports).

In general, the in Chapter 3 provided definition will be used throughout the research as scope for taxiway systems. In the end, for the case study of AAS, only 'handelsverkeer' is taken into account, since for these flights more extensive information and data is available publicly.

1.5 RESEARCH QUESTION

In order to decline the described scientific gap and to reach the research objective, the following Research Question has been defined:

What are challenges and opportunities towards improving airport taxiway systems?

For answering the research question, the following Sub Questions (SQs) will be answered:

SQ 1 How is the taxiway system integrated in the ATS and Airport System?

SQ 2 What are the components of taxiway systems and how are taxiway systems developed and designed?

SQ 3 What are taxiway systems' actors and how do they use the system?

SQ 4 Which KPIs should be used for assessing the performance of the taxiway system and how can they be measured?

SQ 5 Which assessment methods should be used for assessing the performance of taxiway systems on defined KPIs?

SQ 6 How is the taxiway system at AAS being used?

SQ 7 What do processes within the taxiway system at AAS look like?

SQ 8 Which stakeholders are involved in the taxiway system at AAS?

SQ 9 How does the taxiway system of AAS perform on the defined safety KPI?

By answering these ten SQs, an answer to the Research Question can be formulated. Figure 1.3 on page 6 summarizes the inducement of this research.

1.6 RESEARCH APPROACH

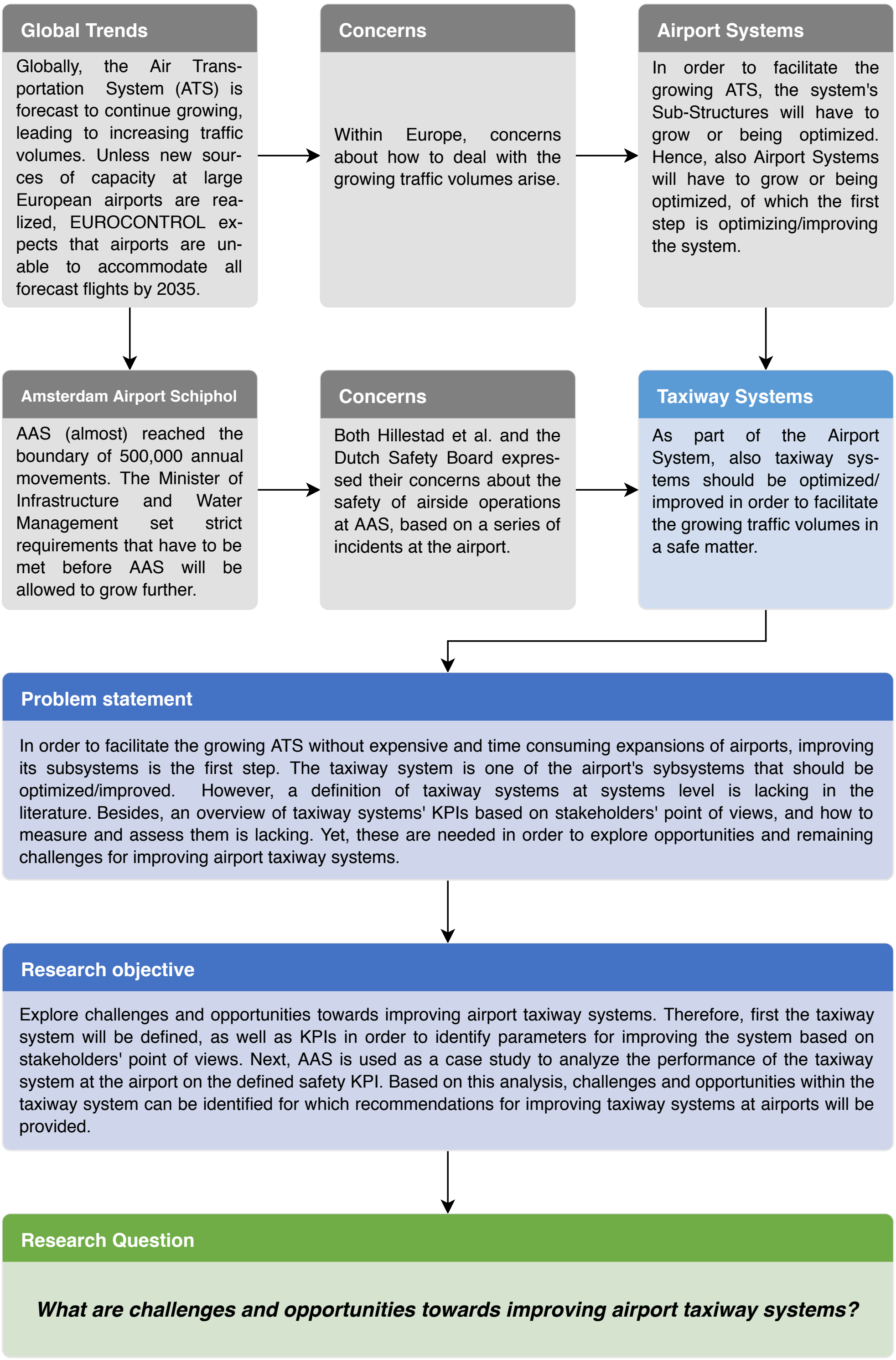
As shown in Figure 1.4, the research is setup in two phases. In the first phase (blue blocks), taxiway systems are explored: a definition of taxiway systems is provided based on literature research and interviews. Besides, KPIs for taxiway systems are defined (including assessment methods) based on literature research and interviews, in order to place safety into perspective of other indicators.

The second phase (yellow blocks) focuses on the case: AAS. After exploring the taxiway system of AAS, the airport's taxiway system is analyzed on safety following the defined assessment method for the safety KPI. Each of the (sub-)phases will answer one or more SQs, as shown in Figure 1.4.

In the end, conclusions and recommendations are provided based on the case study for taxiway systems in general, as well as for AAS.

The framework shows both the process flow, as well as the data flow of the research. As can be seen, three types of data inputs are used: literature review, interviews and occurrence report data. In Chapter 2, the applied methodologies are elaborated in detail.

The research is performed at the Airport Civil Engineering department of NACO (Netherlands Airport Consultants). Within NACO, extensive knowledge on airport planning and design in present. This study is valuable for NACO to obtain further insights on taxiway systems, in order to improve airport layouts and to design new airports' taxiway systems and improve existing taxiway systems. For the researcher, executing the research at NACO brings easy access to extensive knowledge of experts and contacts with stakeholders in the aviation industry.



Global Trends

Globally, the Air Transportation System (ATS) is forecast to continue growing, leading to increasing traffic volumes. Unless new sources of capacity at large European airports are realized, EUROCONTROL expects that airports are unable to accommodate all forecast flights by 2035.

Concerns

Within Europe, concerns about how to deal with the growing traffic volumes arise.

Airport Systems

In order to facilitate the growing ATS, the system's Sub-Structures will have to grow or being optimized. Hence, also Airport Systems will have to grow or being optimized, of which the first step is optimizing/improving the system.

Amsterdam Airport Schiphol

AAS (almost) reached the boundary of 500,000 annual movements. The Minister of Infrastructure and Water Management set strict requirements that have to be met before AAS will be allowed to grow further.

Concerns

Both Hillestad et al. and the Dutch Safety Board expressed their concerns about the safety of airside operations at AAS, based on a series of incidents at the airport.

Taxiway Systems

As part of the Airport System, also taxiway systems should be optimized/improved in order to facilitate the growing traffic volumes in a safe matter.

Problem statement

In order to facilitate the growing ATS without expensive and time consuming expansions of airports, improving its subsystems is the first step. The taxiway system is one of the airport's sybsystems that should be optimized/improved. However, a definition of taxiway systems at systems level is lacking in the literature. Besides, an overview of taxiway systems' KPIs based on stakeholders' point of views, and how to measure and assess them is lacking. Yet, these are needed in order to explore opportunities and remaining challenges for improving airport taxiway systems.

Research objective

Explore challenges and opportunities towards improving airport taxiway systems. Therefore, first the taxiway system will be defined, as well as KPIs in order to identify parameters for improving the system based on stakeholders' point of views. Next, AAS is used as a case study to analyze the performance of the taxiway system at the airport on the defined safety KPI. Based on this analysis, challenges and opportunities within the taxiway system can be identified for which recommendations for improving taxiway systems at airports will be provided.

Research Question

What are challenges and opportunities towards improving airport taxiway systems?

Figure 1.3: Inducement of the research

1.7 REPORT STRUCTURE

This master thesis is built up as follows: first the applied methodologies are elaborated in Chapter 2. Afterwards, the remainder of this master thesis is structured following the phases as shown in Figure 1.4. Hence, Chapter 3 provides a definition for taxiway systems. Next, KPIs for taxiway systems are identified in Chapter 4. The case of AAS and how its taxiway system is being used is explored in Chapter 5. Based on several inputs, Chapter 6 analyzes AAS's taxiway system on the defined safety KPI. Afterwards, in Chapter 7 conclusions are drawn and recommendations are provided, thereby answering the Research Question. Eventually, a discussion and reflection on the research is provided in Chapter 8.

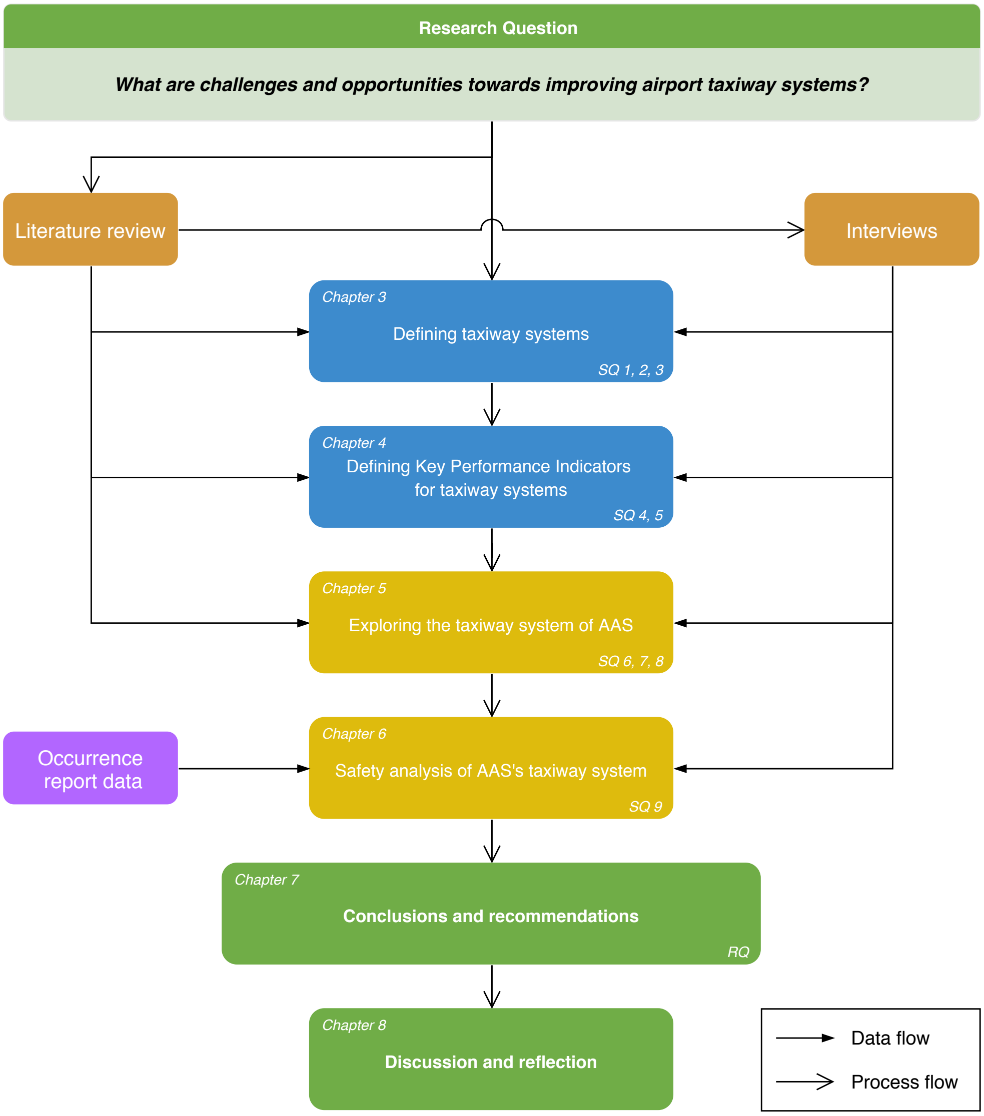


Figure 1.4: Research framework

2 RESEARCH APPROACH AND METHODOLOGY

The research employs a mixed-method approach: although primarily qualitative research is applied, it also comprehends quantitative research. The qualitative research is applied throughout the first phases of the research in order to define the taxiway system, identify Key Performance Indicators (KPIs) and explore the usage of the taxiway system at Amsterdam Airport Schiphol (AAS). Also, qualitative research is used to identify problems within the taxiway system as faced by stakeholders. Next, through more quantitatively research, occurrence report data is analyzed. This chapter further elaborates on the used methodologies.

2.1 LITERATURE REVIEW

Neuman (2014) addresses a cliché to describe the main goal of a literature review: do not waste time "reinventing the wheel". It is important to learn from and build on what others have done. The literature review in this research has two goals, based on the goals described by Neuman (2014): Firstly, to *integrate and summarize what is known in an area*. The literature study gives insights in what is known about the system and what how it being used in practice. Secondly, to *demonstrate a familiarity with a body of knowledge and establish credibility*. The readers should have confidence in the researchers professional competence, ability, and background.

Besides, Neuman (2014) defines six types of literature studies, of which two are be used in this research:

1. *Context review:* By performing this type of literature study, the study can be introduced by situating it within a broader framework and showing how it continues or builds on a developing line of thought or study;

2. *Integrative review:* This type of literature study enables the author to present and summarize the current state of knowledge on a topic.

During the literature study, multiple types of literature were used.

Literature published in journals (papers) was searched by using a combination of different search engines. Scopus, Science Direct and Google Scholar were all used to find relevant scientific papers about the topic. Examples of keyword that wer used are: taxiway(s), system, Air Transportation System, airport(s), design, operation, Key Performance Indicator, AAS, safety. Additionally, search operators such as AND and OR were used. Moreover, both forward and backward snowballing were used to search for relative literature. To ensure external validity, only peer reviewed papers are used.

Next to scientific papers, also (technical) reports were used. One important report in airport design is ICAO's Annex 14 to the convention of International Civil Aviation, in which Standards and Recommended Practices (SARPs) for the design and operations of Aerodromes are defined (ICAO, 2018a). Besides, other International Civil Aviation Organization (ICAO) publications were used. Furthermore, published procedures by AAS and AIP The Netherlands were used.

2.2 INTERVIEWS

For the qualitative research, next to literature review, interviews are a suitable method. Through interviews, open ended questions can be asked, and individual experiences or opinions regarding the topic of research can be explored. In qualitative research, interviews are primarily semi-structured or unstructured, since they mainly focus on the interviewee's experience and opinion, aiming to get in-depth information (Bryman, 2012). Besides, Silverman (2000) states that exploratory studies should be less structured than confirmatory studies. Since this research primarily has an exploratory character, rather open questions can be used. Hence, the interviews were conducted as conversational survey interviews. In this by Neuman (2014) defined flexible technique, the researcher is able to adjust interviewing questions to the understanding of specific respondents by maintaining the intent in each question. Additionally, other questions might be asked during interview to further discuss certain issues or to clarify specific subjects. However, a basic structure is used to ensure that important issues were covered in the conversation.

Nonetheless, like other methods, the interview-methodology has its limitations. Since interviews are socially constructed, they are constrained by the particular interview situation (Pole and Lampard, 2002). Hence, they are of an artificial character and can therefore not be expected to *"uncover the truth or the essence of individual belief, experience or opinion"* (Pole and Lampard, 2002, p. 127).

Before conducting the interviews, a start was made with the literature review. By doing so, gain insights from literature could be used as a source for interview questions. In order to prepare efficient interviews, the defined questions were distributed into different categories: general questions and actor specific questions. Due to the semi-structured character of the study, it seemed to be logical to let the interviewees answer the questions in an unconstrained way, mentioning everything that came into their mind. Hence, often interviewees bought up themes that were part of later questions. In that case related questions were asked earlier, in regard to the mentioned topic.

All interviews have been conducted in Dutch, the native language for all interviewees. With permission of the interviewees and guaranteeing them anonymity, the interviews were voice recorded to enable transcription afterwards. The transcripts were used for analyzing the interviews.

For the purpose of this master thesis research, nineteen individuals were interviewed. The found actors as mentioned in Chapter 1 by Wilke et al. (2014) were used as a starting point to find relevant stakeholders: pilots, Air Traffic Controllers (ATCOs), ground handlers (of less importance for the taxiway system), airport operators and authorities. Besides, two airport consultants were interview to gather insights on the planning and design aspects of taxiway systems as well. Individuals were approached through different channels. Some were NACO-contacts, others were contacted through the internet, for instance via *LinkedIn*, or had a wider connection. Hence, as shown in Figure 1.4, conducting the interviews was an iterative process, since several interviewees referred to new relevant interviewees.

In order to increase the validity of the research, for most actors more than one interviewee was interviewed, preferably with different functions in order to gain broad insights. Therefore, pilots of different airlines and aircraft types, ATCOs active at different airports, airport representatives of different sizes of airports within the Benelux and different kind of airport consultants were interviewed. An overview of interviewees is presented in Table 2.1.

Transcripts of the interviews can be obtained in a separate booklet (Appendix I), except the transcript of the interview with the Dutch Safety Board, which is not available for publication.

Group	Interviewee	Representing
Pilots	Pilot 1	Captain B737 KLM and representative of the VNV
	Pilot 2	First Officer B787 TUI
	Pilot 3	Captain Embraer 175/190 KLM Cityhopper
	Pilot 4	Captain A320-family
ATC	Air Traffic Controller 1	Ground/Tower controller at skeyes (Brussels)
	Air Traffic Controller 2	Former Dutch military ATCO
	Apron Controller	Apron Controller at AAS
Airports	Asset Manager 1	Airside Works Manager at Brussels
	Asset Manager 2	Asset Manager Continuity runways and taxiways at AAS
	Asset Manager 3	Airport Developer at AAS
	Asset Manager 4	Manager Projects & Infrastructure at MAA
	Operations representative 1	Process owner in- and outbound (including taxiways) at AAS
	Operations representative 2	Airport Manager at GAE
	Operations representative 3	Service owner aircraft (including taxiways) at AAS
	Former director corporate strategy	Former director corporate strategy/master planning at AAS
Ground Handler	Tow truck driver	Tow truck driver for KLM at AAS
Authority	Dutch Safety Board	Senior researchers at the Dutch Safety Board
Airport Consultants	Airport Engineer	Airport Civil Engineer at NACO
	Airport Planner	Airport Master Planner at NACO

Table 2.1: Overview of interviewees

Despite the relative large number of interviewees, a number of remarks should be made to Table 2.1:

- Pilots are all of different airlines, but representing all major airlines at AAS and of which one also is representing the VNV. Moreover, both Narrow Body aircraft (NaBo) and Wide Body aircraft (WiBo) pilots are represented.
- As can be seen in Table 2.1, no 'Ground'-controller of AAS is represented in the interviews. Unfortunately, despite contacting them in different ways, Air Traffic Control the Netherlands (LVNL) was not open for interviews. In order to cover ATCOs opinions, other ATCOs were interviewed. In the end, ATCOs with different functions are represented: Apron Control (AAS), Ground/Tower (Brussels) and former Ground/Tower (military).
- For airport representatives, representatives of four different airports in the Benelux, of three different development stages (see Section 3.4) were interviewed. Besides, both asset management and operations related representatives were interviewed: Brussels (*stage e*), asset management; AAS (*stage f*), both operations and asset management; Maastricht Aachen Airport (MAA) (*stage a/b*), asset management; Groningen Airport Eelde (GAE) (*stage a/b*), operations. Moreover, a former director of corporate strategy of AAS was interviewed.
- It should be noted that the Dutch Safety Board was interviewed - although they are not an authority their selves. However, the board investigates aviation incidents and reports to the government. Considering their report on safety at AAS (Dutch Safety Board, 2017), an interviews was conducted eventually. The transcript of this interview is not available for publication.
- In the end, consultants of both the Airport Civil Engineering and Master Planning department of Netherlands Airports Consultants (NACO) were interviewed.

2.3 OBSERVATIONS

Next to literature research and interviews, observations are used as qualitative research method. Observations are valuable for gaining insights on how people within the system see and understand their surroundings and how they interact with others (Wilkinson and Birmingham, 2003). Both structured and unstructured observations (Research Methodology, 2019) are used in this research: Via LiveATC (2020), live Air Traffic Control (ATC) at AAS has been listened to gather information on procedures and habits. Several times, the 'Ground'-frequency has been listened in general (unstructured) to obtain insights in communications. Besides, some specific information on procedures was obtained by focusing on specific situations in the process (structured). Since no historical data was available for this research, Flightradar24 (2019) has been consulted regularly in order to gain insights on often used taxi routes at AAS.

2.4 PROCESS EXPLORING

Wasson (2015) states that the first step in Systems Engineering (SE) is getting insights on (1) *who* a system's stakeholders are, (2) *what* they expect the system to accomplish, and (3) *how well* the outcome is to be achieved in terms of performance. This is a critical step and it forms the basis for deriving a system from which specification requirements can be derived.

In order to explore the processes, Wasson (2015) suggests to use Unified Modeling Language (UML), which was initially developed for modeling software architecture problems. Nonetheless, more and more UML is used as SE for other fields as well. In 2008, Ahmad and Saxena used UML to design ATC-systems. In this thesis, UML will be used to identified use cases within taxiway systems (use case diagram) and to explore how these processes (use cases) look in more detail (activity diagram).

2.4.1 Use case diagram

A use case diagram captures a system's functionality as seen by its users (Ahmad and Saxena, 2008) and gain insights in the system's functional requirements (Fowler, 2003). Through an outside-in view, it shows the possible procedures in the use of the system and the involved actors and their relation to the use cases.

Figure 2.1 shows an example of a use case diagram and the possible elements in order to explain the methodology. The example and explanations are based on Booch et al. (1999) and Fowler (2003).

The rectangular box shows the systems' boundaries. On the left side, primary actors (end users) are shown. Secondary actors are shown on the right side of the system. Besides, actors can be specified into general kinds of actors and more specialized actors. The actors in that case can be related through generalization. Within the ovals, the use cases are shown. In case an actor is involved in a use case, the association is shown by a line. Use cases can also have relationships between each other. An include relationship between use cases means that the the base use case incorporates the behavior of another use case. The included use case never stands alone, but is only instantiated as part of a larger use case. The included use case can be recognized by a dashed outgoing arrow pointing at its base use case with the text <<include>> attached to the arrow. An excluded relationship between use cases means that under certain circumstances, the base use case incorporates the behavior of another use case. The excluded use case can be recognized by a dashed outgoing arrow pointing at its base use case with the text <<extend>> attached to the arrow.

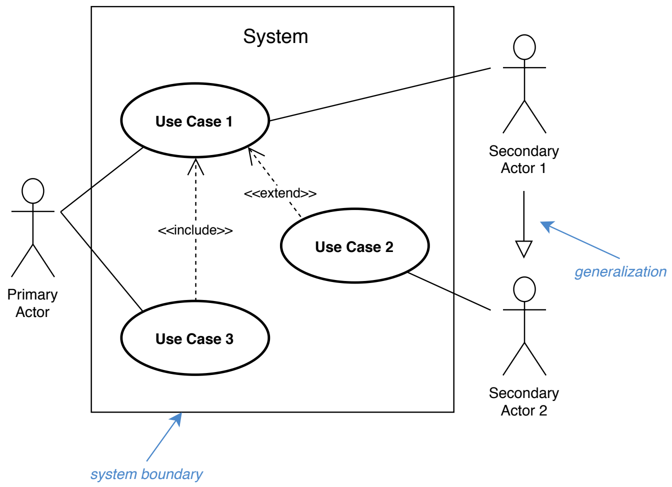


Figure 2.1: Use case diagram elements

The use cases for taxiway systems are similar for each airport. However, their relations to actors might differ per airport.

2.4.2 Activity diagram

Through an activity diagram, a flow of control form activity to activity is shown. It is also referred to by Wasson (2015) as 'swimming lane diagram', since the diagram includes a 'swimming' lane for each involved actor. Figure 2.2 shows an example of a use case diagram and the possible elements in order to explain the methodology. The example and explanations are based on Booch et al. (1999) and Fowler (2003).

Activity diagrams start with an *initial state* and end with a *final stage*. The core elements of an activity diagram are the action states: the actual undertaken actions by the actor. Once an action state is completed, the arrow targets the next step. Optionally, action states can contain a fork, indicating an included use case or activity. Next to action states, signals can be sent and accepted, depicted with slightly different boxes, as can be seen in Figure 2.2. Besides, concurrent forks and joins can be used. Activities after a concurrent fork can be executed simultaneously. However, the process can only continue once all actions with arrows coming in at the concurrent join are completed. In the example as shown in Figure 2.2, the process can only continue once both *action state 2* and *action state 3* are completed. Moreover, branches can be used. These are shown by a rhombus. Each rhombus-outgoing arrow is labeled to show the criteria for the branch.

For activity diagrams, it should be noted that they are airport specific.

2.5 STAKEHOLDER ANALYSIS

As mentioned before, getting insights in *who* a system's stakeholders are is a critical step in SE (Wasson, 2015). A stakeholder analysis helps to evaluate and understand stakeholders from their perspective and determine their relevance to the system (Brugha and Varvasovszky, 2000). In this thesis, a stakeholder analysis will be performed for the taxiway system of AAS. Therefore, the interviews with AAS-related interviewees are the major input for the stakeholder analysis. Besides, the literature review is used to gain understanding of involved stakeholders.

Hence, firstly, a list of stakeholders is determined and their objectives and goals within the taxiway system is provided. Secondly, a power-interest grid is constructed. From this grid, it becomes graphically visible which stakeholders are the key players in the system.

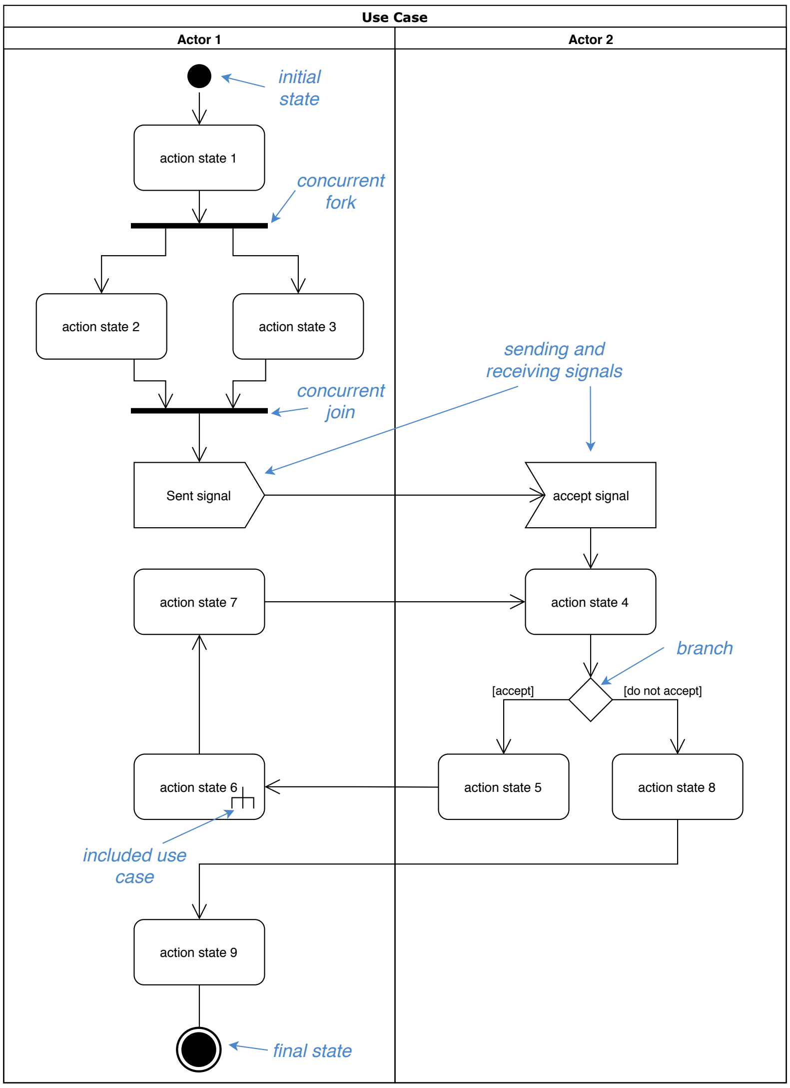


Figure 2.2: Activity diagram elements

2.5.1 Power-Interest grid

Freeman (1984) was the first to identify power and interest as significant dimensions for a grid. Ackermann and Eden (2011) refined the by Freeman developed power-interest grid and defined four quadrants which they identified as categories of stakeholders. The four stakeholder categories as defined by Ackermann and Eden (2011) are: Players (high power and high interest), Context setters (high power, low interest), Subjects (low power, high interest), and Crows (low power, low interest). Murray- Webster and Simon (2006) defines *power* as the stakeholders power or ability to influence the system's organization, either derived from the potential to influence from their resource or positional power, or from their actual influence from their credibility as a leader or expert. The stakeholder's *interest* is the extent to which a stakeholder will be active or passive (Murray- Webster and Simon, 2006).

2.6 OCCURRENCE REPORT DATA ANALYSIS

The Dutch Inspectie Leefomgeving & Transport (*Human Environment and Transport Inspectorate*) (ILT), as part of the Ministry of Infrastructure and Water Management, is responsible for monitoring the safety and environmental impact of aviation in

The Netherlands. Since 2014, through regulation No 376/2014 of the European Union, occurrence reports are collected in a central database (European Union, 2014). However, already in 2009 the ILT was collecting occurrence reports. In these reports, users (e.g. pilots, ATCOs, ground handlers) report occurrences in aviation.

The occurrence report data will in this thesis be used to verify the identified problems within the taxiway system of AAS as experienced by interviewed stakeholders on data. This section will elaborate on the content of the data and how it was used.

2.6.1 Data contents

Through a formal request, data from the national database of the ILT was obtained. Data was filtered by the ILT on the following criteria:

- Reports on or after 1 January 2009;
- The location indicator equals "EHAM", or the 'location name' field contains "schiphol", "eham", or "Amsterdam" (capital insensitive);
- At least one of the free text fields ('headline', 'narrative' or 'reporter's description') contains at least one of the following words: "taxi", "taxiway", "taxibaan", or "taxiing", or the field 'flight phase has the value "Taxi".

Besides, the released data is build up of the following columns:

- File number
- Headline
- UTC date
- Local data
- State/area of occurrence
- Location name
- Location indicator
- Occurrence class
- Occurrence category
- Narrative text
- Narrative language
- Reporter's description
- Event type
- Risk classification
- Manufacturer/model
- Aircraft type
- Propulsion type
- Mass group
- Maximum t/o mass
- Flight phase
- Weather conditions
- Weather relevant
- Weather report
- Location on aerodrome
- Highest damage
- Injury level

The data was obtained as Excel-sheet. After the filtering by the ILT, the data consisted of 12,875 rows. However, the ILT mentioned several notes by delivering the data Van der Wal (2019):

- The data file contains technical duplicates - multiple rows with the same file number;
- The data file contains substantive duplicates, since different parties can report the same occurrence;
- Not all fields are filled or reliably filled;
- Through the years, legal requirements on reporting as well as reporting behaviour has changed.

2.6.2 Data preparation

In order to reduce the data set, two steps were undertaken. First, to prevent usage of duplicates, rows with the equal file numbers are merged. Hence, in case one of the column values does not equal, the text is replaced by 'multiple'. After this first step, the data set consisted of 9,029 occurrence reports.

Secondly, to eliminate occurrences that have no relation to the operation or the design of taxiway systems, reports that meet the following criteria were eliminated:

- At least one of the free text fields 'headline', 'narrative' or 'reporter's description' contains at least one of the following key-words: "passenger", "pax", "hot brakes", "technical problem", "fuel", "FMS", "open door", "CA1", "aborted", "blast", "parking", "neuswiel", "takeoff", "take off", "take-off", "SOP", "found", "object", "water", "incursion", "trailer", "door", "closed", "GPU", "APU", "ENG", "steering", "aileron", "technisch", "pieces", "piece", "parts", "steel", "steal", "tyres", "docking", "self-docking", "crew", "gate", "VOP", "brand-/rookmelding", "seatbelt", "turbulence", "tractor", "truck", "take off clearance", "transponder", "nose wheel", "approach", "ILS-approach", "birdstrike", "push-back", "pushback", "push back", "runway incursion";
- If the text field 'event type' contains at least one of the following key-words: "Aircraft return", "Push-back", "birdstrike";
- If the text field 'flight phase' contains at least one of the following key-words: "approach", "take-off".

After this second preparation step, the data set consisted of 2,178 occurrence reports. Both steps were executed through Python programming.

In the European repository, occurrences shall be reported if they fall into one of the following four categories (European Union, 2014):

(a) Occurrences related to the operation of the aircraft (e.g. collision-related);

(b) Occurrences related to technical conditions, maintenance and repair of the aircraft;

(c) Occurrences related to air navigation services and facilities (e.g. (near) collisions, specific occurrences or operational occurrences);

(d) Occurrences related to aerodromes and ground services (e.g. related to ground equipment).

Based on these categories, nine more specific categories were defined, to enable more detailed analysis. Below the categories are elaborated, including on which category of the European repository it is based:

1. ***ATC*** (based on (c)): Deviation from standard procedures by ATC;
2. ***Lacking ATC*** (based on (c)): Guidance of ATC is lacking;
3. ***Flight Crew*** (based on (a)): The flight crew deviates from the instruction of ATC or a standard procedure;
4. ***Other vehicle*** (based on (d)): An occurrence of an aircraft with another vehicle (no aircraft), e.g. tow movements on taxiways or service vehicle or ambulances on intersections of taxiways with service roads;
5. ***Failure*** (based on (b)): A failure within the taxiway system, such as Foreign Object Debris (FOD);
6. ***Taxi speed*** (based on (b)): The flight crew exceeds the allowed taxi speed;
7. ***Technical issue*** (based on (b)): A technical issue with the aircraft;

8. ***Pushback/docking*** (based on (d)): An occurrence during pushback or docking at the stand;

9. ***Other***: All other occurrences.

Each report is manually categorized into the above defined categories. However, Technical issue, pushback/docking and other are outside the scope of this research and will therefore not be used in the data analysis.

2.6.3 Data analysis

Once the data set is prepared for analysis, the intended analysis can be performed: a black spot analysis of occurrences in the taxiway system. Therefore, within the free text fields, a search should be performed on location identifiers. Moreover, a word cloud can be created of the prepared data set. A word cloud can provide insights on often used words which might indicate certain problems as well.

2.7 OVERVIEW

Table 2.2 shows an overview of the applied methods per research phase. The table also shows the distribution of phases over the chapters and which Sub Questions (SQs) are answered within the phase.

Chapter	Phase	Answered SQs	Applied Methods
3	Defining taxiway systems	1, 2, 3	• Literature review • Interviews • Observations • Process exploring
4	Defining KPIs for taxiway systems	4, 5	• Literature review • Interviews
5	Exploring the taxiway system of AAS	6, 7, 8	• Literature review • Interviews • Observations • Process exploring • Stakeholder analysis
6	Safety analysis of AAS's taxiway system	9	• Interviews • Occurrence report data

Table 2.2: Overview of the used methodologies

3 THE TAXIWAY SYSTEM

Currently, no clear and comprehensive definition of taxiway systems is available in the literature. Therefore, this chapter aims to provide a definition for taxiway systems. During the interviews, all interviewees were primarily asked what comes up in their mind when thinking about a taxiway System. The answers were all in line: *'the whole of taxiways that connect the aprons and runways.'* Besides, repeatedly given answers were *'safety'*, *'guidance'* and *'capacity'*. Those keywords are in line with what (ICAO, 2005b) indicates as the major functional requirement of a taxiway system: "enabling a smooth, continuous flow of aircraft ground traffic at the maximum practical speed with a minimum of acceleration or deceleration to and from the runways and apron areas." Besides, (ICAO, 2005b) states that the taxiway system should always be able to accommodate the demands of aircraft arrivals and departures on the runway system. In other words, the capacity of the operational taxiway system should always exceed the capacity of the operational runway system.

To be able to define and further understand taxiway systems, the V-model as provided by Schmitt and Gollnick (2016) will be used (from high level to low level) in the remainder of this chapter. Hence, first, general remarks on global differences are provided in Section 3.1. Second, the phases of flights are discussed in Section 3.2, with special attention for ground operations. Third, one level deeper in the V-model as provided by Schmitt and Gollnick (2016), components of the taxiway system are identified and explained in Section 3.3. Next, the focus is on development and design of taxiway systems. Therefore, fourth, in Section 3.4 the development of taxiway systems for an airport over time is discussed. Fifth, in Section 3.5 design characteristics of taxiway system components are provided. Afterwards, sixth, Section 3.6 elaborates on general procedures for usage of the taxiway system as defined by ICAO. Seventh, the different related actors of taxiway systems and their major purposes are outlined in Section 3.7. To conclude, eventually, a definition of the taxiway system is proposed in Section 3.8.

This chapter is based on literature research and interviews with pilots, airport representatives, ATCOs and airport consultants.

3.1 GLOBAL DIFFERENCES

On many aspects, global differences in airport design and operations can be found. Major inequalities can be found between the USA and Europe (de Neufville and Odoni, 2013). Where in Europe ICAO and corresponding European Union Aviation Safety Agency (EASA) standards (based on ICAO standards) are used for airport design, the United States applies the standards as developed by the Federal Aviation Administration (FAA). The ICAO and FAA standards are similar in general, but also differ in some important aspects.

Besides, FAA and Eurocontrol (2012) mention that (Air Traffic Management (ATM)-related) procedures differ. In Europe, when traffic demand is expected to exceed the available capacity (either en route or at airports), ATC can call for "Air Traffic Flow Management (ATFM) Regulations". If an aircraft is subject to these regulations, it is held at the departure airport according to"ATFM slots": the flight gets a Calculated

Take Off Time (CTOT), which is allocated by the Central Flow Management Unit (CFMU) of Eurocontrol.

Moreover, during the interviews all pilots and the airport consultants stated that clear difference amongst taxiway systems within Europe can be found. From a planning and design perspective differences are caused by economical situations. Richer regions have more money to spent on higher quality and safety than poorer regions. Within the existing infrastructure at some airports, the pilots mention, the infrastructure (e.g. pavements or lighting) is of lower quality. Also ATC-communication quality differs. Especially in Southern-European countries the quality of English communication falls short. Most important, the pilots state, is the difference amongst individual airports, which is also emphasized by the airport consultants. Airports with one runway or two parallel runways are (for example) often more predictable in relation to taxiing than airports with more or conflicting runways. In other words, each airport has its own and specific characteristics.

3.2 FLIGHT PHASES

To get insights on how the taxiway systems is used within the Air Transportation System (ATS), a general overview of the phases of a flight is provided. Four core flight phases can be identified: (1) arrival, (2) ground operations, (3) departure, and (4) en-route. Next to the interviews, the descriptions of the phases are based on literature by Kageyama and Fukuda (2008); Lee and Balakrishnan (2010); Jiang et al. (2013) and ICAO (2013a). Please note that the descriptions are general, and not AAS-specific.

3.2.1 Arrival

The arrival of a flight at an airport starts with the approach. The approach for Instrument Flight Rules (IFR)-flights is split up in three core parts: Initial Approach (from Initial Approach Fix (IAF) to Final Approach Fix (FAF)), Intermediate approach and Final Approach. For Visual Flight Rules (VFR)-flights, the approach starts at 1000 feet (300 meters) above the runway end elevation or at the point of VFR pattern entry to the flare above the runway. Afterwards, the landing begins once the flight crew receives a landing approval by ATC. The landing lasts until the aircraft exits the landing runway[1], comes to a stop or when power is applied for takeoff in the case of a touch-and-go landing (whichever comes first).

3.2.2 Ground operations

All activities on the ground can be considered as ground operations. The identified phases within the ground operation will be elaborated below.

Arrival taxi

Once touched down, aircraft should leave the runway as quickly as possible in order to reduce runway occupancy time and maximize the runway capacity and safety. Therefore, many airports use Rapid Exit Taxiways (RETs). After leaving the runway[1], the flight crew contacts the airport's/ATC's ground control for taxi instructions and they complete the "after landing taxi" checklist. The aircraft manoeuvres under own power to the apron[2]. Depending on the airport layout, sometimes (a) part(s) of

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[1] Leaving the runway is defined to start at the moment the cockpit of the aircraft intercepts the Center line marking of the taxiway used for leaving the runway.

[2] Definition **Apron**: *"A defined area, on a land aerodrome, intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fuelling, parking or maintenance."* (ICAO, 2018a)

the taxi route may consist of a (non-)active runway. In case the gate is not available yet, the arriving aircraft may have to wait at a (remote) holding location until the assigned gate becomes available. Once clearance to the gate is received, the aircraft moves into the ramp area and there enters the aircraft stand[3].

Ground arrival process

Once the aircraft is aircraft is parked at a stand and the blocks are applied, the ground handling process begins. First of all passengers are deplaned and baggage and freight are unloaded, depending on the type of flight.

Intermediate parking and towing

Since the ground handling process comprehends different activities, aircraft can eventually be assigned to different gates for the different processes (ground arrival process and ground departure process) if necessary or advantageous . In the case that an aircraft is assigned to different gates for the different processes, the aircraft has to be relocated by a towing tractor. Besides, in case there is a long period between the scheduled arrival time and the scheduled departure time (e.g. over 3 hours), gate planners can decide to park the aircraft temporarily at a buffer stand. Three advantages of splitting and/or parking flights at a buffer stand are identified in the literature: First, it provides extra flexibility. Second, extra capacity becomes available at gates for assigning other aircraft. Third, flights with different regions for origin and destination (i.e. domestic/international or Schengen/Non-Schengen) can be assigned to two single-region gates as they do not have to be assigned to the same gate. Towing also is required in case an aircraft will get larger maintenance before executing its next flight. This is especially the case for aircraft on their base airport. The aircraft is in this case towed to the maintenance hangar.

Ground departure process

To prepare the aircraft for departure, several actions have to be fulfilled: cleaning and catering the aircraft, performing required security checks, refueling the aircraft, and finally, boarding the passengers and loading baggage and freight. In some cases, despite the boarding of passengers and loading of baggage and freight, the process is executed at the intermediate parking position.

Besides, in case of winter conditions, the aircraft might have to be de-iced (see Section 3.6.2). Depending on the procedures at an airport, this can be done at the stand or at a specific de-icing apron. In the latter case, during departure taxi from the apron to the runway, the aircraft has to taxi via the (assigned) de-icing apron.

Pre-departure

When the ground handling process is completed and the departing flight is ready for pushback and receives pushback clearance from ATC, the aircraft is pushed out of the stand[4]. After the towing vehicle is disconnected and the aircraft's engines are started, the flight crew contacts 'Ground'-control/ATC to get taxi clearance and routing information to the assigned departure runway.

Departure taxi

Once taxi clearance is received, the flight crew starts taxiing the aircraft out on its own power[4]. Depending on the layout of the airport, taxiing aircraft may have to wait and ask for clearance before crossing specific points in the airport

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[3] Definition **Aircraft stand**: *"A designated area on an apron intended to be used for parking an aircraft."* (ICAO, 2018a)

[4] Stands can also be designed in a way that no pushback is needed (taxi-in/taxi-out stands). In this case, after receiving clearance, the aircraft starts the Departure Taxi from the stand on its own power.

infrastructure, like (active) runways. Besides, an aircraft may experience delays before the takeoff if there are many departures ahead of it in the takeoff queue. Alternatively, if the flight is assigned a CTOT, the aircraft may be routed via a (remote) holding location and wait there until it receives clearance to taxi to the departure runway. Depending on the airport layout, sometimes a part of the taxi route may consists of either (another) (non-)active runway or the assigned active departure runway (e.g. in case there is no full parallel taxiway available up to the runway turn pad). Once the aircraft reaches the runway, the flight crew should first receive clearance to line up on the runway. The departure taxi stage ends when the flight crew applies takeoff power.

As mentioned before, in case of winter conditions and depending on the airport procedures, the aircraft might have to taxi via the (assigned) de-icing apron before taxiing to the assigned departure runway.

3.2.3 Departure

After lining up and receiving takeoff clearance, the flight crew applies takeoff power. The takeoff run is defined as the takeoff roll and rotation up to 35 feet (12 meters) above the runway elevation or until gear-up selection, whichever comes first. From there, the initial climb starts. The initial climb ends when reaching 1000 feet above the runway elevation or the VFR pattern, or at the first prescribed power reduction, whatever comes first.

3.2.4 En-route

After finishing the initial climb, the en-route flight phase begins with the climb to cruising altitude or level, followed by cruising. Within the cruising phase, the aircraft might be assigned an increased or decreased cruising altitude. The cruise flight ends at the start of the descent toward the destination airport. The en-route flight phase ends at the beginning of the approach, the start of the arrival.

3.3 COMPONENTS

The deepest level of the V-model for the ATS as defined by Schmitt and Gollnick (2016) are components. In this section, the components of the subsystem 'Taxiway System' are discussed. First, the components for the V-model are described: the physical components. Second, sub-components are described. These are denoted as part of the taxiway system by the interviewees. In the end, other (non-physical) components are described.

Physical Components

In Annex 14, ICAO (2018a) identifies and defines three types of taxiways: *Taxiways, Apron taxiways,* and *Aircraft stand taxilanes*, of which the first and the last also were identified by the interviewees. These are the core components of the taxiway system. Besides, based on Annex 14 (ICAO, 2018a), the before described flight phases (Section 3.2) and the interviews, additional physical components (*RETs*, *holding bays* and *runway turn pads*) were identified as part of the taxiway system.

Below, the systems' physical components are defined, mainly based on (ICAO, 2018a, p. 1.11):

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.

Apron taxiway
A portion of a taxiway system located on an apron and intended to provide a through taxi-route across the platform.

Aircraft stand taxilane
A portion of an apron designated as a taxiway and intended to provide access to aircraft stands only.

Holding bay
A defined area where aircraft can be held, or bypassed, to facilitate efficient surface movement of aircraft.

Rapid Exit Taxiway (RET)
A taxiway connected to a runway at an acute angle and designed to allow landing aeroplanes to turn off at higher speeds than are achieved on other exit taxiways thereby minimizing runway occupancy times.

Runway turn pad
A defined area on a land aerodrome adjacent to a runway for the purpose of completing a 180-degree turn on a runway. Instead of a runway turn pad, also a taxiway turnaround can be provided to facilitate a 180-degree turn at the end of a runway.

In addition to the above listed components, those sections of the runway were the center line of the entry/exit taxiway continues on the runway are part of the taxiway system. These parts are overlapping areas of the taxiway system and Runway System. Since on these sections the aircraft is defined to be taxiing (see Section 3.2), they are included as physical component of the taxiway system as '**Overlap entry/exit runway**'.

Besides, in case no full parallel taxiway is constructed along a runway, an arriving or departing aircraft might have to use larger parts of the runway for taxiing towards the runway turn pad. In these situations, the runway should be considered as part of the taxiway system as well. However, since a runway's core function is facilitate takeoff and landings and since runways are part of the Runway Systems, they are not permanently considered as component of the taxiway system.

The above mentioned taxiway system's components are illustrated in Figure 3.1.

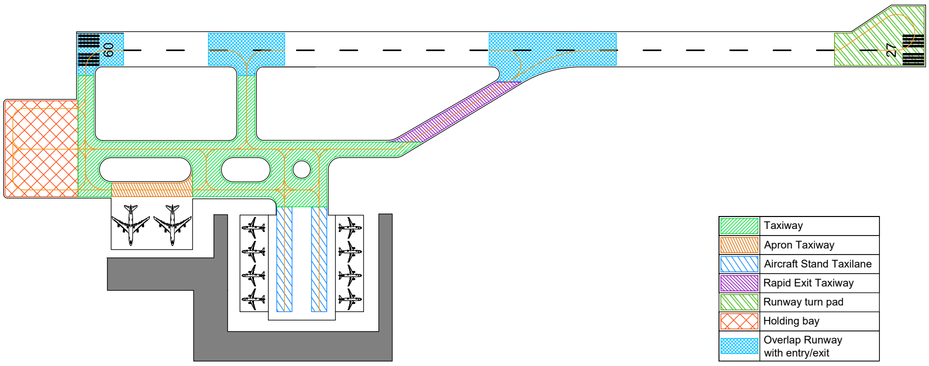

Figure 3.1: Overview of the taxiway system components (adapted from ICAO (2005b))

Moreover, interviewees mentioned markings, lighting and signs as component of the taxiway system. These are referred to as **visual aids** and are considered to be a component of the taxiway system as well.
As mentioned before, the physical components are considered as components in the ATS-breakdown as defined by Schmitt and Gollnick (2016). Now these components of the taxiway system are known, a breakdown of the ATS on the four system levels of the ATS as described by Schmitt and Gollnick (2016) focusing on the taxiway system can be defined (see Figure 3.2).

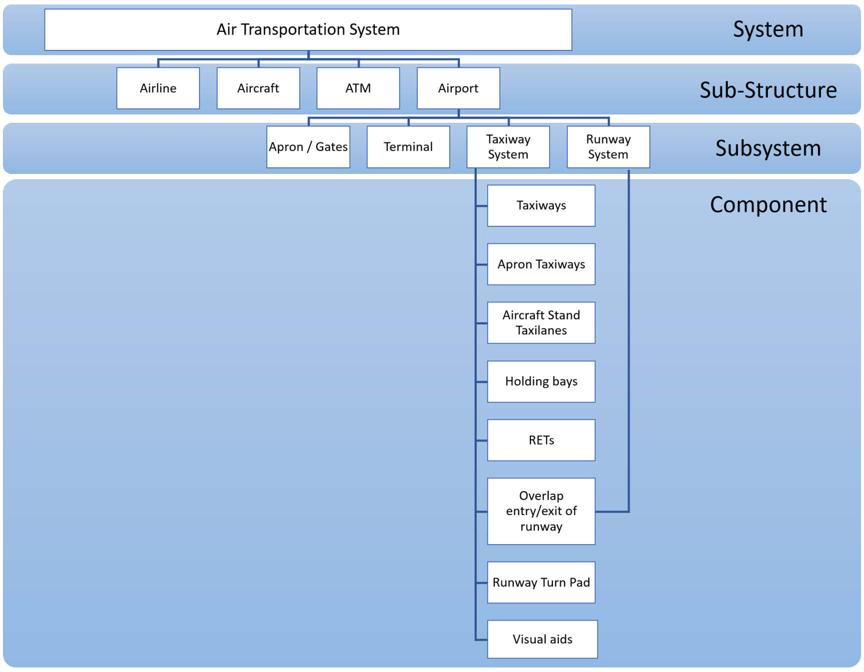

Figure 3.2: Air Transportation System Breakdown, based on ICAO (2018a); Oostra (2019); Schmitt and Gollnick (2016)

Other components

Next to the above described physical components, the interviewees mentioned other components as part of the taxiway system. Since ATCOs provide guidance of aircraft over the taxiway system, several interviewees also suggest to consider ATC as a part of the taxiway system. Besides, within the design *drainage* of the taxiways plays an important role, as well as the *(pavement) construction*.

In order to increase safety at the airport surface, airports indicate hot spots[5]. These are highlighted on the airport map as used by the flight crews to make them aware of potential risk. Hence, hot spots are no physical components. Hot spots are generally defined in cooperation between the airport and ATC.

One final (non-physical) component of the taxiway system that was mentioned by interviewees is designation (names) of taxiway systems' components.

3.4 TAXIWAY SYSTEM DEVELOPMENT

For the development of taxiway systems, ICAO (2005b) defines several stages. In order to minimize the construction costs, they state that an airport's taxiway system should only be as complex as needed to support the near-term capacity needs of the airport. However, in doing so, careful planning is needed to be able to add

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[5] Definition **Hot spot**: *"A location on an aerodrome movement area with a history or potential risk of collision or runway incursion, and where heightened attention by pilots/drivers is necessary."* (ICAO, 2018a)

taxiway components to the system in later stages when the demand of the airport grows. In Figure 3.3, the six stages as defined by ICAO are shown. Below, the stages are described (ICAO, 2005b, p. 1.4 - 1.7):

a) a minimum aerodrome taxiway system, supporting a low level of runway utilization, can consist of only runway turn pads at both ends of the runway and a stub taxiway from the runway to the apron;

b) traffic growth which results in a low to moderate level of runway utilization may be accommodated by building a partial parallel taxiway to connect one or both turnarounds (parallel taxiways provide safety benefits as well as greater efficiency);

c) as runway utilization increases, a full parallel taxiway can be provided by completing the missing sections of the partial parallel taxiway;

d) exit taxiways, in addition to the ones at each runway end, can be constructed as runway utilization increases toward saturation;

e) holding bays and bypass taxiways can be added to further enhance runway capacity. These facilities seldom restrict the attainment of full aerodrome capacity within the existing aerodrome property because land is usually available to permit their construction; and

f) a dual-parallel taxiway, located outboard of the first parallel taxiway, should be considered when movement in both directions along the taxiway is desirable. With this second taxiway, a one-way flow network can be established for each direction of runway use. The need for the dual-parallel system increases in proportion to the amount of development alongside the taxiway.

Despite the described stages in development of taxiway systems, de Neufville and Odoni (2013) state that practice does not always strictly follow this principle. They state that, in airfield design, often the taxiway system is an after-thought: *"the positioning and configuration of the runways and landside facilities is done and afterwards the taxiway system is designed to provide connections between the runways and the apron areas."* (de Neufville and Odoni, 2013, p. 300)

The interviewed airport consultants partly agreed on this statement. The Airport Planner emphasizes the importance of looking at the airport system as an integral assignment, where also the taxiway system plays a critical role. Yet, he concedes that most attention is payed to bottle necks within the airport, which is often not the taxiway system. The Airport Engineer mentioned that changing the taxiway system is easier than changing the terminal and runways, also within a design project.

3.5 TAXIWAY DESIGN

In ICAO's Annex 14 (ICAO, 2018a) and in corresponding Document 9157 (ICAO, 2005b), Standards and Recommended Practices (SARPs) for the physical design of taxiway system's components are provided. Similarly, EASA published the Certification Specifications and Guidance Material for Aerodromes Design (EASA, 2017). The specifications and recommendations of EASA are based on the ICAO documentations. Therefore, the following sections of this thesis are based on the SARPs by ICAO.

Besides, order to design airport's infrastructure efficiently, ICAO (2018a) defines aerodrome reference codes. Aerodrome infrastructure should be designed based on the critical aircraft code which the aerodrome should facilitate. This code is build up of two elements: the first on aircraft performance (reference field length), and the second aircraft design (wingspan). For taxiway design, only the latter is of importance. In Table 3.1 the aircraft code letters and corresponding wingspans are shown.

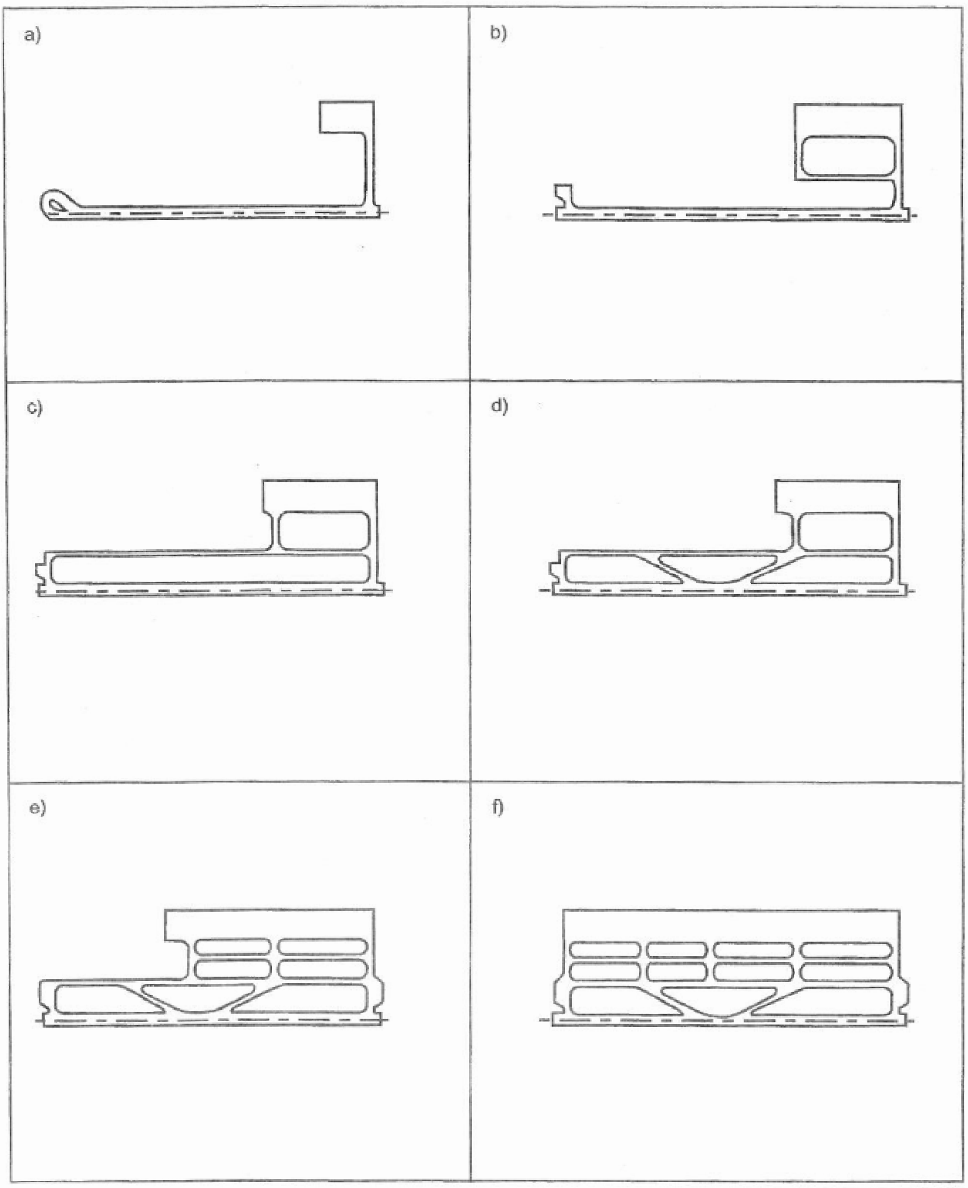

Figure 3.3: Stages in development of a taxiway system (ICAO, 2005b)

Code letter	*Wingspan (ws)*
A	ws <15 m
B	15 m $\geq$ ws <24 m
C	24 m $\geq$ ws <36 m
D	36 m $\geq$ ws <52 m
E	52 m $\geq$ ws <65 m
F	65 m $\geq$ ws <80 m

Table 3.1: Aircraft code letters (ICAO, 2018a)

3.5.1 Taxiways, Apron Taxiways and Aircraft stand Taxilanes

In Annex 14 (ICAO, 2018a) and related part 2 of document 9157 (ICAO, 2005b), definitions, SARPs for the design of Taxiways, Apron Taxiways and Aircraft stand Taxilanes are provided for the following elements:

- Width of taxiways
- Taxiway curves
- Junctions and intersections
- Minimum separation distances
- Slopes (longitudinal/transverse)
- Sight distances
- Strength of taxiways
- Surface of taxiways
- Taxiway shoulders
- Taxiway strips
- Holding positions

In this thesis, only the most relevant elements will be discussed. For other elements, the writer refers the reader to ICAO's Annex 14.

Width of the taxiways

To enable safe movement of aircraft, ICAO defined minimum clearances between the outer main wheel of the aircraft and the edge of the taxiway, which shall be met when the cockpit of the aircraft for which the taxiway is intended remains over the taxiway center line markings (Section 3.5.5). These clearances are defined based on the aircraft's Outer Main Gear Wheel Span (OMGWS). Withing the range, always the largest OMGWS should be used. Besides, the wheel base [6] may play a role.

	OMGWS			
	<4.5 m	≥ 4.5 m, <6 m	≥ 6 m, <9 m	≥ 9 m, <15 m
clearance	1.50 m	2.25 m	3 [7] m or 4 [8] m	4 m

Table 3.2: Clearances for taxiway width (ICAO, 2018a)

Hence, the width of a straight taxiway for aircraft with an OMGWS of 6m is 15m: 9m as the largest OMGWS in the range, plus twice (left and right) the corresponding clearance of 3m.

Separation distances

Clearances are defined for safe separation per aircraft code for all taxiways, other than aircraft stand taxilane (Taxiway Clearance), and aircraft stand taxilanes (Taxilane Clearance), see Table 3.3.

Aircraft code letter	*Taxiway clearance*	*Taxilane clearance*
A	8 m	3 m
B	8 m	3 m
C	8 m	4.5 m
D	11 m	7.5 m
E	11 m	7.5 m
F	11 m	7.5 m

Table 3.3: Clearances for taxiway separations (ICAO, 2018a)

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[6] Wheel base means the distance from the nose gear to the geometric center of the main gear.

[7] Either on straight portions or on curved portions for aircraft with a wheel base <18 m.

[8] On curved portions for aircraft with a wheel base ≥ 18 m.

Based on these clearances and the maximum allowed wingspan (*ws*) of an aircraft at the intended taxiway, separations can be determined for:

- Taxiway center line to taxiway center line:
  $2 \cdot 1/2\ ws$ + *Taxiway clearance*
- Taxiway center line to object:
  $1/2\ ws$ + *Taxiway clearance*
- Aircraft stand taxilane center line to aircraft stand taxilane center line:
  $2 \cdot 1/2\ ws$ + *Taxilane clearance*
- Aircraft stand taxilane center line to object:
  $1/2\ ws$ + *Taxilane clearance*

It should be noted that clearances of aircraft may overlap.

Below, two examples of separation distances within the taxiway system are given:

1. Distance between two Taxiways, on which at maximum code E aircraft can taxi (all aircraft with wingspan <65m):
   The distance equals $2 \cdot 1/2\ ws$ *+ Taxiway clearance:* $65m + 11m = 76m$.
2. Width of a aircraft stand taxilane between two stands, on which at maximum an aircraft with a wingspan of 29m can taxi:
   The width in this case equals twice the distance from the center line to an obstacle (in this case the back of a stand). The aircraft code for this aircraft is C. Hence, the width equals $2 \cdot (1/2\ ws$ *+ Taxilane clearance):* $2 \cdot (1/2 \cdot 29m + 4.5m) = 38m$.

Taxiway shoulders

Taxiways may be provided with shoulder stabilization. These shoulders have the appearance of pavement but are not intended to support aircraft. Shoulders help to prevent blast and water erosion as well as to provide a smooth surface that can be kept free of FOD.

Holding positions

ICAO (2018a) distinguishes three types of holding positions: (1) runway-holding positions, (2) intermediate holding positions and (3) road-holding positions. At these holding positions, aircraft have to receive clearance from ATC before crossing.

Runway-holding positions shall be established on the taxiway at the intersection of a taxiway and a runway, and at intersections of two runways when one of the runways is part of the standard taxi-route. Besides, runway-holding positions shall be placed on a taxiway if the location of the taxiway is such that a taxiing aircraft can interfere with the operation of radio navigation aids of the runway or infringe its obstacle limitation surface.

An intermediate holding position should be created on a taxiway at any point (other than a runway-holding position) where it is desirable to define a specific holding limit.

At an intersection of a (service) road with a runway, a road-holding position shall be established. Road-holding positions consist of lights, markings and signs. Hence, where a (service) road intersects a taxiway, a road-holding position is not obligated. Yet, depending on the operational conditions, in practice airports can decide to apply road-holding positions at intersections of a (service) road and a taxiway. Since it is not obligated, also the details of the fulfillment can be determined by the airport.

3.5.2 Holding bays

At larger airports (>50,000 annual movements), an adequate number of holding bay spaces or other bypasses allows a large degree of flexibility in the operation. It provides ATC with greater flexibility in adjusting the takeoff sequence to overcome undue delays, thus increasing the capacity of an airport. Besides, holding bays may be used to hold aircraft after landing when the assigned stand is not yet available.

3.5.3 Rapid Exit Taxiways

Part 2 of ICAO's document 9157 (2005b) provides extensive information on designing RETs. As can be seen in Figure 3.4, the main parameters in designing RETs are the intersection angle (preferably 30 degrees), radius of turn-off curve (large enough to enable the aircraft to make the turn at relatively high speeds) and straight distance of the RET (which should be long enough to enable the aircraft to decelerate to a normal taxi speed).

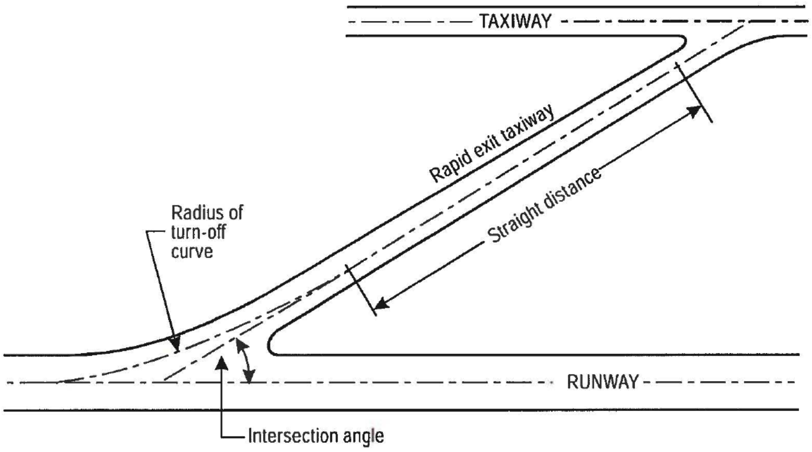

Figure 3.4: Design elements of RETs (ICAO, 2018a)

3.5.4 Runway Turn Pad

In case the end of a runway is not served by a taxiway and the runway should facilitate aircraft of code letter D, E or F, a runway turn pad shall be provided to facilitate a 180-degree turn of aircraft. For aircraft of code letter A, B, and C ICAO only recommends to use runway turn pads in this case.

Runway turn pads may be located on either the left or the right side of the runway. However, the left side of the runway is preferred, since the left seat is the normal position of the pilot-in-command.

3.5.5 Visual aids

ICAO refers to markings, lighting and signs as 'Visual Aids'. SARPs on visual aids are provided in Annex 14 (ICAO, 2018a). Besides, detailed SARPs are provided in document 9157 part 4 - Visual Aids (ICAO, 2004). Below, core specifications for each of these visual aids are briefly described.

Markings

In order to provide continuous guidance during taxiing, *taxiway center line marking* shall be provided on paved taxiways. The taxiway center line marking shall be located along the taxiway center line on straight sections. In curves, the marking should continue from the straight portion of the taxiway at a constant distance from the outside edge of the curve. In Appendix C basic and enhanced taxiway center line markings are shown in Figure C.1 and Figure C.2.

In order to show the edges of the taxiway and the boundaries between taxiways and taxiway shoulders, *taxiway side stripe markings* may be provided. Moreover, in curves and at intersections confusion between the side stripe markings and center line markings may exist or the flight crew may be unsure on which side of the edge marking the non-load bearing pavement (shoulder) is. Therefore, in these areas transverse stripes on the shoulders can be provided as assistance (see Figure C.3).

Other types of markings are runway-holding positions markings (see Figure C.4) and information markings. The latter can be used to provide the pilots of information via markings instead of or in addition to signs. An information (location or direction) marking can be displayed prior to and following complex taxiway intersections and/or where operational experience has indicated that information markings could assist flight crew for ground navigation.

Lighting

On taxiways intended for use in Runway Visual Range (RVR)[9]-conditions less than a value of 350 meters, *taxiway center line lights* shall be provided. For all taxiways intended to be used at night, ICAO (2018a) recommends to apply taxiway center line lights as well. Yet, under these conditions taxiway center line lights are not needed when taxiway edge lights and center line marking provide adequate guidance. Besides, ICAO notes that taxiway center line lights are not necessarily needed to be provided when the traffic density is light.

Taxiway edge lights shall be provided at the edges of runway turn pads, holding bays and taxiways not provided with taxiway center line lights, all intended to be used at night. Yet, taxiway edge lights need not be provided where, considering the nature of the operations, adequate guidance can be achieved by surface illumination or other means (e.g. *edge markers*). Characteristics of taxiway lights are shown in Figure C.5.

Signs

Two types of signs can be identified: *mandatory instruction signs* and *information signs*. Mandatory instruction signs (see Figure C.6) shall be provided to identify a location beyond which an aircraft taxiing or vehicle shall not proceed unless it is authorized by ATC. They include runway designation signs, category I, II or III holding position signs, runway-holding position signs, road-holding positions sings and 'no entry' signs.

Information signs (see Figure C.7) shall be provided where there is an operational need to identify a specific location, or routing (direction or destination) information by a sign. Information signs can include direction signs, location signs, destination signs, runway exit signs, runway vacated signs and intersection takeoff[10] signs.

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[9] Definition **Runway Visual Range (RVR)**: The range over which the pilot of an aircraft on the center line of a runway can see the runway surface markings or the lights delineating the runway or identifying its center line.

[10] An intersection takeoff is a takeoff from a runway/taxiway intersection, not being on the threshold of the runway, including RETs and runway entries/exits not being on the threshold of the runway.

3.5.6 Designations

ICAO (2018a) states in Annex 14 that each taxiway shall be identified by a designator comprising a letter, letters, or a combination of a letter or letters followed by a number. The use of number(s) alone on the manoeuvring area shall be reserved for the designation of runways, and is thus not allowed for taxiway designations. Besides, ICAO (2018a) recommends to avoid the letters *I*, *O* or *X* and the use of words such as *inner* and *outer* to avoid confusion with the numerals 1, 0 and 'closed taxiway' marking.

3.6 PROCEDURES

This section provides an overview of procedures within the taxiway system. First, basic rules and procedrues for the aviation industry as stated by ICAO are provided. Second, Section 3.6.2 provides insights in winter operations on airports.

3.6.1 General rules and procedures

In Annex 2, ICAO states basic rules and procedures for the aviation industry. For surface movement of aircraft ICAO states the following (ICAO, 2005a, p. 3.2-3.3):

1. In case of danger of collision between two aircraft taxiing on the movement area of an aerodrome the following shall apply:

a) when two aircraft are approaching head on, or approximately so, each shall stop or where practicable alter its course to the right so as to keep well clear;

b) when two aircraft are on a converging course, the one which has the other on its right shall give way;

c) an aircraft which is being overtaken by another aircraft shall have the right-of-way and the overtaking aircraft shall keep well clear of the other aircraft.

2. An aircraft taxiing on the manoeuvring area shall stop and hold at all runway-holding positions unless otherwise authorized by the aerodrome control tower.

3. An aircraft taxiing on the manoeuvring area shall stop and hold at all lighted stop bars and may proceed further when the lights are switched off.

Since these rules are limited, airports define additional rules and procedures for their own aerodrome.

3.6.2 Winter operations

The process of winter operations is important for the year-round operation of an airport. In 2010, the majority of European airports were covered by a blanket of ice and snow, caused by arctic conditions (Schmitt and Gollnick, 2016). This put the airports under pressure to maintain runways, taxiways and aprons clear and open for normal flight movements. Hence, planning and preparation of winter operation process are of great importance. The two main procedures within the winter operation process are de-icing of aircraft and cleaning the operational surfaces of the airport. It should be noted that de-icing does not take place within the taxiway system, however impacts the taxiway system due to possible additional taxi movements.

De-icing

In critical weather conditions (temperatures below 0° Celsius and/or snow/cold rain fall), proper prevention and removal of ice from aircraft is critical for safe operations (de Neufville and Odoni, 2013). If ice would be build up on the wings and tail of the aircraft, the aerodynamic flow around the lifting surfaces could change. This could degrade the performance of the aircraft during takeoff (Schmitt and Gollnick, 2016). Therefore de-icing/anti-icing fluids are sprayed on the wings and tail of the aircraft (see Figure 3.5), which melt existing and inhibit the further formation of snow and ice. Most of the used fluids contain toxic elements (glycol). Therefore, de-icing has to be done on locations on the airport were the fluid can be collected separately for recycling.

Figure 3.5: De-icing of an aircraft (Schiphol, 2019a)

Cleaning of operational surfaces

The airport authority takes care of the mechanical clearing of the snow with ploughs and cutter blowers and also the chemical de-icing of operational surfaces (Schmitt and Gollnick, 2016). Every airport has its own procedures for these activities.

3.7 ACTORS

This section provides a brief overview of actors involved in taxiway systems. Since responsibilities vary over different airports, the overview of actors in this section remains at a high (general) level. In Section 5.6, an extensive stakeholder analysis is provided for AAS.

A use case diagram captures a system's functionality as seen by its users (Ahmad and Saxena, 2008). Through an outside-in view, it shows the possible use cases of the system, including variants (Booch et al., 1999). Based on the in Section 3.2 defined flight phases for ground movements on airports and the identified physical components of taxiway systems, the use cases related to taxiway systems can be identified. In Figure 3.6, the developed use case diagram for taxiway systems is shown.
The identified main use cases are *Departure taxi*, *Arrival taxi*, *Towing*. Besides, *infrastructure works* (e.g. maintenance or cleaning of operational surfaces) shall be possible. Within the Departure and Arrival taxi use cases, *Taxiing* is an included use case and *Holding* is an extended use case. Moreover, within the Departure taxi, *De-icing* is an excluded use case. As mentioned before, de-icing itself does not necessarily

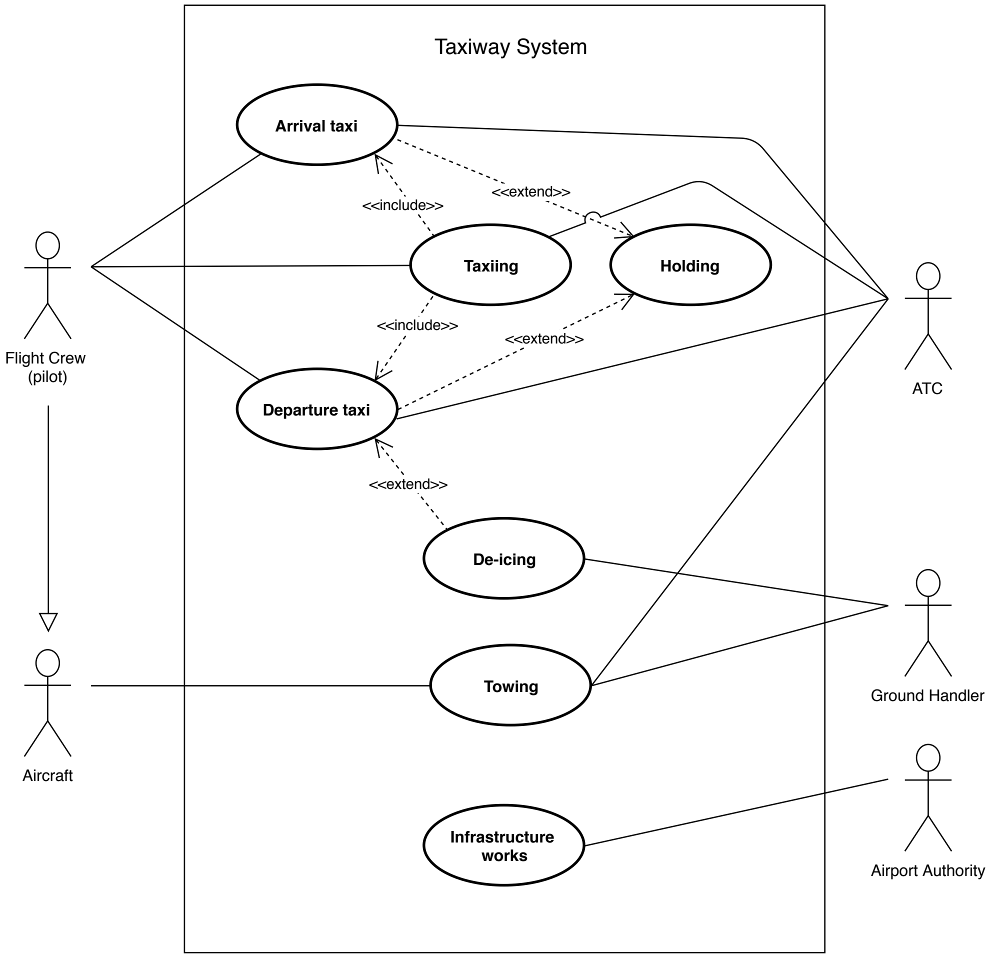


Figure 3.6: General Use Case diagram of a taxiway System

take place within the taxiway system, but it might require additional movements within the taxiway system and is therefore considered in the use case diagram.

From the use case diagram, now the related actors can be identified: the *aircraft* and *Flight Crew*, *ATC*, the *Ground Handler* and the *airport*. This list of actors is in line with the by Wilke et al. (2014) identified five stakeholders for Airport surfaces: Pilot (*aircraft and flight crew*), ATC, Vehicles and Pedestrians (V/PD) (*Ground Handler*) and Airport Operator (*Airport*). Wilke et al. (2014) add regulators (e.g. ICAO and EASA) and Environment and external stakeholders, which will all be referred to as *indirect actors*, since they do net directly act within the taxiway System. Below, the purpose of each actor is explained.

Aircraft and Flight Crew

The aircraft is the end user of taxiway systems: aircraft movements on the airport's surface are enabled by taxiway systems, either under its own power (taxi) or by a tow-truck (towing). When an aircraft moves under its own power (most of the time), it is controlled by the flight crew (pilot). Therefore, the Flight Crew is one of the actors, but can be generalized to the the actor aircraft. During towing, no flight crew has to be present in the aircraft, only a representative of the Ground Handler should be in the cockpit to control the aircraft's brakes.

All pilots stated that they prefer the taxiway System to be as easy as possible with clear guidance from ATC in order to enable safe movements. Besides, they prefer to limit the taxi time as much as possible.

Airport

The physical taxiway System (generally) is an airport's asset. Hence, the airport facilitates the use of the taxiway System. They are therefore also responsible for maintenance and providing sufficient capacity. The airport's goal is to find a balance between sufficient capacity and minimizing operating costs while facilitating safe movements of aircraft.

ATC

Within the taxiway System, ATC can be seen as both a user and enabler. ATCOs use the airport's infrastructure and by guiding aircraft they enable them to manoeuvre on the airport's surface.

Every airport under ATC-guidance has a 'Tower'-controller. The 'Tower'-controller is responsible for separation of aircraft during takeoffs and landings. At smaller airports, the 'Tower'-controller can also be responsible for the guidance of ground movements of aircraft. For larger airports, often next to the 'Tower'-controller a 'Ground'-controller is used. In that case the 'Ground'-controller is responsible for all ground movements, and the 'Tower'-controller is responsible for movements at the runways (landings and takeoffs). Once an airport becomes even busier, additional'Tower'- and 'Ground'-controllers can be employed. In that case areas of responsibility are assigned to each ATCO. Within the Benelux, only AAS and Brussels Airport make use of multiple 'Tower'- and 'Ground'-controllers.

In case multiple ATCOs are simultaneously operating, also multiple ATC-frequencies should be available. For example, at Brussels Airport two 'Ground'-controllers can be active simultaneously. Two different 'Ground'-frequencies will be used in that case.

Ground Handler

Within the taxiway System, the ground handler operates the towing truck when aircraft are towed. Depending on the airport size, one or more ground handlers can be active. Ground handlers can be commercial parties which are active at multiple airports, a subsidiary of an airline, a airport specific party or part of the airport authority.

Indirect actors

There are two major indirect actors: *Authorities* and *local residents*. The Authorities regulate the airport, and thus indirectly also the taxiway System. Local residents living around the airport are often represented in consultative bodies for airport hindrance.

3.8 CONCLUSION: TAXIWAY SYSTEM DEFINITIONS

To conclude this chapter, based on the in this chapter gained knowledge on taxiway systems, a definition of the taxiway system is provided:

The taxiway system is that part of the aerodrome surface movement area intended for safely connecting runways with aprons and facilitating all other movements of aircraft other than takeoff or landing under guidance of ATC.

In order to make the definition more specific, it is split up in two parts: an operational definition and a physical definition.

3.8.1 Operational definition Taxiway System

The taxiway system is operationally used under guidance of ATC:

- *for arriving aircraft from the moment the cockpit of the aircraft intercepts the center line marking of the taxiway used for exiting the runway, maneuvering over the airport surface on its own power, until the aircraft crosses the ATC service boundary;*
- *for departing aircraft from the moment the aircraft starts maneuvering over the airport surface on its own power, until takeoff power is applied on the runway; or*
- *when aircraft are being towed in a forward direction by a towing truck.*

3.8.2 Physical definition Taxiway System

The physical taxiway system exists of those surfaces of an airport within the ATC service boundary, excluding the runway, and being either a taxiway, apron taxiway, aircraft stand taxilane, holding bay, RET, runway turn pad or overlap of the entry/exit from/to the runway, including the related sub-components, being visual aids, drainage infrastructure and the (pavement) construction.

By providing a comprehensive definition of the taxiway system, the first objective of this research is achieved and SQs 1, 2, and 3 are answered. Next, KPIs for the taxiway system are defined in Chapter 4. The provided definition of the taxiway system will be used as scope for this research.

4 TAXIWAY SYSTEMS' KEY PERFORMANCE INDICATORS

In scientific literature, only Key Performance Indicators (KPIs) for the Airport system in general are discussed, not for taxiway systems in specific. Nonetheless, Annex 14 of ICAO (2018a) and the corresponding Document 9157 (ICAO, 2005b) provides specific requirements for taxiway systems. Besides, information from scientific literature can partially be used for taxiway systems as well, since the taxiway system is a subsystem of the Airport (Figure 3.2). Hence, this section will combine ICAO's requirements with literature and retrieved information from the interviews to define KPIs for taxiway systems. Yet, first the principles of KPIs, what they are and what they can be used for, will be discussed.

In the literature, comparable definitions of KPIs can be found. The KPI Institute (2018) defines KPIs as follows: *"A measurable expression for the achievement of a desired level of results, in an area relevant to the evaluated entity's activity. KPIs make objectives quantifiable (...)"* (The KPI Institute, 2018, p. 18)

Similarly, Chan and Chan (2004) define the purpose of KPIs as enabling measurement of project and organizational performance. Based on Collin (2002), Chan and Chan describe characteristics of KPIs (Chan and Chan, 2004, p. 209-210):

- KPIs are general indicators of performance that focus on critical aspects of outputs or outcomes;
- Only a limited, manageable number of KPIs is maintainable for regular use;
- The systematic use of KPIs is essential as the value of KPIs is almost completely derived from their consistent use over a number of projects;
- Data collection must be made as simple as possible;
- For performance measurement to be effective, the measures or indicators must be accepted, understood and owned across the organization;
- KPIs will need to evolve and it is likely that a set of KPIs will be subject to change and refinement.

For the measurement of KPIs, Chan and Chan (2004) distinguish *objective* and *subjective* measures. The objective measurements can be done through mathematical formulas and calculations, they can quantitatively be measured. The subjective measurements are opinions and personal judgements of stakeholders (e.g. quality, functionality, satisfaction). In order to quantify these qualitative measurements, Chan and Chan (2004) suggest to use a seven-point scale scoring system.

Although The KPI Institute (2018) and Chan and Chan (2004) do not focus on the Air Transportation System (ATS), their descriptions can be used for airports as well. Andersson Granberg and Munoz (2013) focus on KPIs for airports. They mention that Airport KPIs are used to measure the most important aspects of the airport and that KPIs can both be quantitative or qualitative measures with possibly different structures and units. Besides, Andersson Granberg and Munoz (2013) state that KPIs do not provide a detailed analysis, or directly suggest how to improve the airport, but can be used as pointers, showing where more work has to be performed.

Hence, the in Section 4.3 defined KPIs can be used for finding subjects within taxiway systems that need more work to be improved.

4.1 GENERAL INDICATORS

Now it is known what KPIs are, first an overview of based on the interviews and literature identified general indicators for assessing taxiway systems is provided:

- Safety
- Complexity
- Capacity
- Environmental impact
- Dependency
- Robustness
- Flexibility
- Availability
- Standards compliance
- Traffic demand
- Quality of procedures
- Quantity of infrastructure
- Quality of infrastructure

In Table 4.1, per interview the mentioned indicators are checked. Besides, it is shown which of the identified indicators are found in the literature.

	Pilots				ATC			Airports, Asset Management				Airports, Operations			Airport, planning	Ground Handler	Authority	Airport Consultants			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Air Traffic Controller 1	Air Traffic Controller 2	Apron Controller	Asset Manager 1	Asset Manager 2	Asset Manager 3	Asset Manager 4	Operations representative 1	Operations representative 2	Operations representative 3	Former director corporate strategy	Tow truck driver	Dutch Safety Board	Airport Engineer	Airport Planner	*Literature*	*TOTAL*
Safety	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	18
Complexity	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓		✓			✓	✓		✓	14
Capacity					✓			✓	✓	✓		✓		✓	✓	✓			✓	✓	10
Environmental impact																				✓	1
Dependency	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓						✓	✓		13
Robustness						✓		✓	✓	✓		✓	✓	✓	✓				✓		9
Availability						✓		✓	✓	✓		✓	✓	✓					✓		8
Flexibility				✓	✓	✓	✓					✓	✓	✓				✓	✓		9
Standards compliance				✓		✓		✓	✓	✓	✓	✓	✓	✓				✓	✓		11
Traffic demand	✓	✓		✓	✓			✓	✓	✓	✓	✓	✓								10
Quality of procedures	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓						✓		13
Quantity of infrastructure	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓		14
Quality of infrastructure	✓	✓	✓	✓		✓		✓	✓		✓	✓		✓			✓	✓	✓		13

Table 4.1: Overview of mentioned indicators per interview

From the list of indicators, four KPIs are identified: safety, capacity, robustness and environmental impact. Those four indicators meet the definition of KPIs: they are considered to be important (*key*), they reflect the achievement of the level of results of a taxiway system (*performance*) and are quantifiable (*indicators*). Yet, quantifying KPIs can be challenging. As mentioned in Chapter 1, concerns on the safety of airside operations raised in the past decades. Therefore, in Chapter 6 the safety within the taxiway system of Amsterdam Airport Schiphol (AAS) will be analyzed. Hence, in the next section, the KPI safety is elaborated, including proposed method of measurement and method of assessment. Afterwards, the other three KPIs are elaborated and explained, including a proposed method of measurement and assessment. Next, the other indicators are described, split up in endogenous and exogenous (inputs) indicators. In the end, conclusions are provided, as well as causal relations of all KPIs and other indicators.

4.2 SAFETY

Safety is widely recognized as critical factor. Within Annex 14 of the International Civil Aviation Organization (ICAO) safety can be seen as the thread (ICAO, 2018a). For taxiway systems, ICAO (2005b) defines Standards and Recommended Practices (SARPs) on the design to ensure the highest level of safety. On its website, the Airport Council International (ACI) states its priorities for the global air transportation. They consider safety as number one priority for airports and the aviation community (ACI, 2019) Also during the interviews, most interviewees mentioned safety as the most important factor (see Table 4.1). They stated that operations have to be safe at all times.

Researchers found safety to be one of the critical KPIs of airport operations too. For example, Baltazar et al. (2018) states that safety characterises a part of the airport's responsibilities. Also Hillestad et al. (1993) underpin the importance of safety as a consideration for organizations associated with aviation management and Boosten (2017) states that maintaining the highest standards of safety at all times is a pre-requisite. Managers of the mentioned organizations should be aware of the economic, moral and societal reasons for maintaining a high standard of safety at airports, Hillestad et al. (1993) state.

Within the aviation industry, it is recognized that accidents in complex systems (like the taxiway system) occur through the concatenation of multiple factors (Reason et al., 2006). Hence, incidents generally do not have one causation, but a set of causes together causing the incident. Wilke et al. (2015) summarizes a number of contributing factors; *human factors, operational practices and procedures* are researched by (amongst others) the European Union Aviation Safety Agency (EASA) and the International Air Transport Association (IATA), while the impact of the airport and its associated characteristics are important as well.

The management of safety at airports has been important ever since aviation started. Throughout the history of airport safety management, four approaches can be described, which roughly align with eras of activity (see Figure 4.1).

In the first half of the twentieth century, aviation emerged as a form of mass transportation in which identified safety deficiencies were initially related to technical factors and technological failures (ICAO, 2018b). By the early 1970s technological improvements and enhancements to safety regulations had led to a gradual decline in the frequency of accidents. The focus in safety endeavours was extended to include human factors, which were increasingly recognized as important contributor

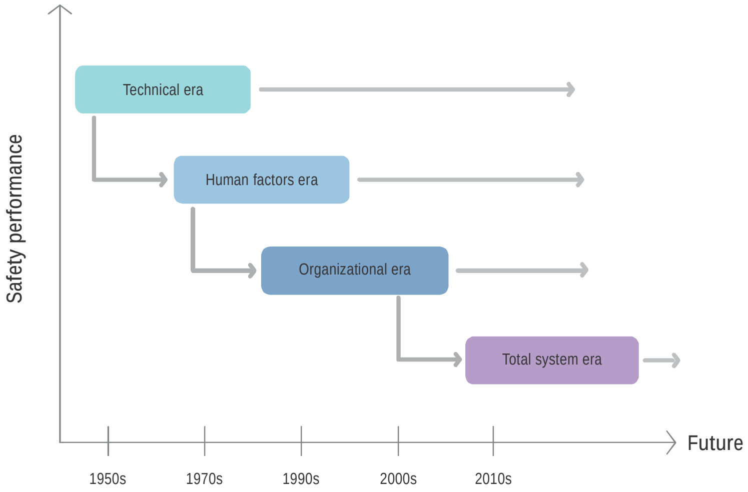


Figure 4.1: Evolution of aviation safety (ICAO, 2018b)

to safety. A number of models have been developed to support the assessment of human factors on safety performance. ICAO (2018b) created the SHELL Model to illustrate the impact and interaction of the different system components on the human.

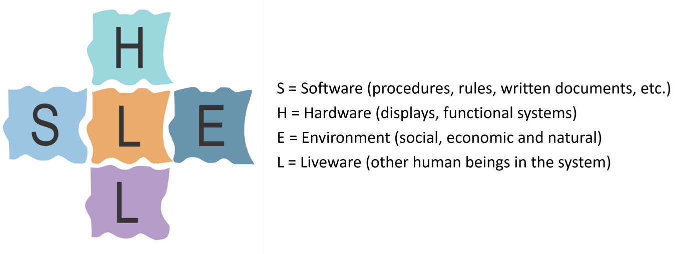


Figure 4.2: SHELL model (ICAO, 2018b)

The SHELL model (Figure 4.2) illustrates the relationship between the human (in the middle of the model) and the four other components. Human errors in the L-L relation, for example, include aspects of communication, organizational culture, support and cooperation. The L-H interaction represents human-machine interface issues. For instance, situations in which communication systems technically are incorrectly used by either a pilot or Air Traffic Controller (ATCO). The L-E interaction covers for example the physical environment (including all physical components as listed in Section 3.3) in which an aircraft operates, and also includes external environmental factors such as noise. An example of the L-S relation is an occasion in which procedures are misunderstood or not followed by the flight crew. As mentioned in Section 3.7, five main actors (liveware-element) are present in the taxiway system.

During the mid-1990s, safety began to be viewed from a systematic perspective and began encompassing, next to technical and human factors, organizational factors as well. Within the organizational aspect of safety, Snook (2000) defined a theory on the 'practical drift' to explain how performance of a system "drifts away" from its original design. Procedures, regulations, and systems are often designed and planned in a theoretical environment, with an implicit assumption that nearly everything can be predicted and controlled (baseline performance). Yet, once operationally deployed, the operational performance (see Figure 4.3) often differs from the assumed baseline performance as a consequence of real-life operations in a complex, ever-changing and usually demanding environment (Snook, 2000). Since the drift is a consequence of daily practice, Snook (2000) refers to it as 'practical drift'. In this context, he uses the term 'drift' as the gradual departure from an intended course due to external influences.

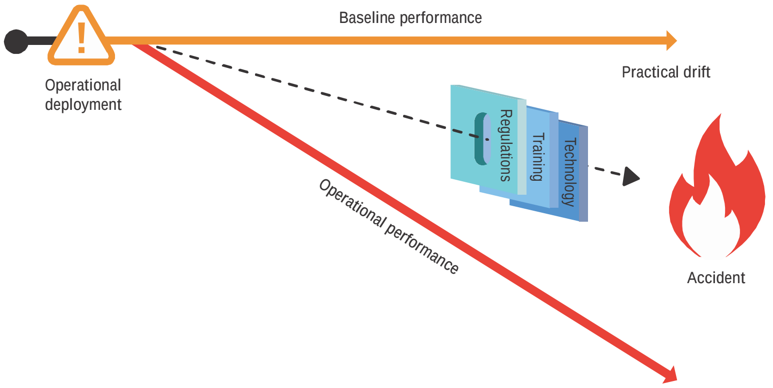
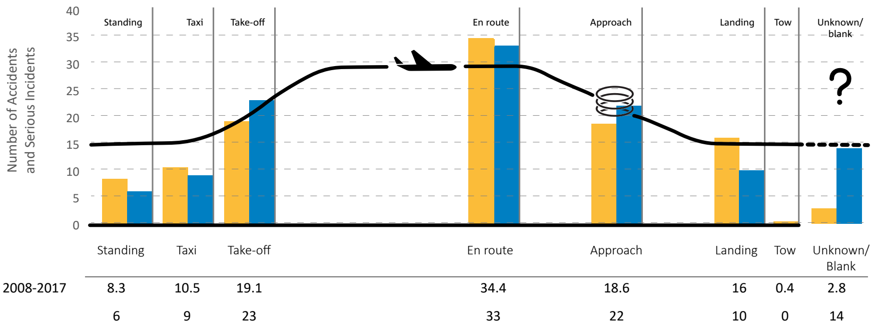


Figure 4.3: Concept of practical drift (ICAO (2018b) based on Snook (2000))

From the beginning of the 21st century, safety started to be considered at a systems level, comprising technical factors, human factors as well as organizational factors. Nonetheless, safety systems have largely focused on individual safety with minimal regard for the wider context of the total ATS. This has led to growing recognition of the complexity of the ATS and the different organizations that all play a role in aviation safety (ICAO, 2018b).

In the last decade (2008-2018), globally on average 10.5 accidents and serious incidents occurred yearly during taxiing (EASA, 2019b), see Figure 4.4. Placing this in perspective of an estimated worldwide air traffic of about 37.8 million movements (Aviation Safety Network, 2019), the rate of accidents and serious incidents during taxiing is one per 3.6 million movements. From this data it can be concluded that the number of accidents and serious incidents during taxiing at a single airport is limited.



	Standing	Taxi	Take-off	En route	Approach	Landing	Tow	Unknown/ Blank
🟨 Average 2008-2017	8.3	10.5	19.1	34.4	18.6	16	0.4	2.8
🟦 2018	6	9	23	33	22	10	0	14

Figure 4.4: Number of accidents and serious incidents by flight phases, 2008-2018 (EASA, 2019b)

From the figures by EASA (2019b), it can be seen that occurrence are often identified as either accident or incident. Below, the definitions of accidents and incidents by ICAO (2016, p. 1-1 and 1-2) are provided. An extensive definition of an accident is provided in Appendix D.

Accident: An occurrence associated with the operation of an aircraft which, in the case of a manned aircraft, takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, or in the case of an unmanned aircraft, takes place between the time the aircraft is ready to move with the purpose of flight until such time as it comes to rest at the end of the flight and the primary propulsion system is shut down, in which:

a) a person is fatally or seriously injured, or

b) the aircraft sustains damage or structural failure, or

c) the aircraft is missing or is completely inaccessible.

Incident: An occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation.

Fortunately, the majority of occurrences within the aviation are incidents (EASA, 2019b). Therefore, ICAO divides incidents into five categories (LVNL, 2019a):

> ***Serious incident***: "An incident involving circumstances indicating that an accident nearly occurred. Note that the difference between an accident and a serious incident lies only in the result."
> ***Major incident***: "An incident associated with the operation of an aircraft in which safety of aircraft may have been compromised, having led to a near collision between aircraft, with ground or obstacles (i.e. safety margins not respected, which is not the result of an ATC instruction)."
> ***Significant incident*** : "An incident involving circumstances indicating that an accident, a serious or a major incident could have occurred if the risk had not been managed within safety margins, or if another aircraft had been in the vicinity."
> ***No safety effect***: "An incident which has no safety significance."
> ***Not determined***: "Insufficient information was available to determine the risk involved, or inconclusive or conflicting evidence precluded such determination."

Besides, for the purpose of occurrence analysis, categorization can be done by the in Section 2.6 defined categories (based on European Union (2014)):

1. ***ATC***: Deviation from standard procedures by Air Traffic Control (ATC);
2. ***Lacking ATC***: Guidance of ATC is lacking;
3. ***Flight Crew***: The flight crew deviates from the instruction of ATC or a standard procedure;
4. ***Other vehicle***: An occurrence of an aircraft with another vehicle (no aircraft), e.g. tow movements on taxiways or service vehicle or ambulances on intersections of taxiways with service roads;
5. ***Failure***: A failure within the taxiway system, such as FOD;
6. ***Taxi speed***: The flight crew exceeds the allowed taxi speed.

Measurement

Several ways to quantify safety are listed in the literature. Andersson Granberg and Munoz (2013) suggest to use the number of aircraft safety incidents in general as measure for safety. Baltazar et al. (2018) prefer to specify the incidents into more detail and use for example the number of Runway Accidents as measure for safety. They define the number of Runway Accidents as: *"Aircraft accidents involving a runway per thousand aircraft movements (take-offs and landings are counted separately), measured over the course of a year."* (Baltazar et al., 2018, p. 224). A similar measure can be defined for taxiway systems.

In order to measure and manage the safety within taxiway systems, a number of adjustments to the method by Baltazar et al. (2018) are required. Since on taxiway systems speeds are relatively low, the impact of occurrences is lower. Therefore, not only accidents and serious incidents should be of interest, but also incidents of lower severity categories should be taken into account. However, data on occurrences of lower severity categories is dependent on reporting data, thereby making measurement sensitive for subjective reporting. A methodology of analyzing Potentially Hazardous Interactions (PHIs) based on processing surveillance radar data as proposed by Ford et al. (2014) might be useful to validate occurrence report data and supplement the data with unreported occurrences. Additionally, since not all types of occurrence have similar impact on safety, the above six described occurrence categories are entailed in the safety measure with specific weight factors. Though, more research is required to identify the exact weight factors. Moreover, the gauge is normalized to *per movement* to enable comparisons amongst airports. In the end, the following method of measurement for safety within the taxiway system at an airport is defined:

$$\textit{Safety}\ [\text{Annual occurrences / movement}] = \frac{\sum_{c \in C} f_c \cdot O_c}{\textit{movements per year}} \tag{4.1}$$

with:
f_c = Weight factor for occurrence category c
O_c = Annual number of occurrence of occurrence category c
C = Set of six occurrence categories as listed on the previous page

Due to time limitations, however, as the weight factors f_c are not yet determined. Therefore, in this research for all occurrence categories f_c will be set to 1, and further research on determination of the weight factors is recommended.

Assessment method

As mentioned before, incidents generally do not have one causation, but a set of causes together causing the incident (Reason et al., 2006). Hence, assessing the safety of a taxiway system is not unambiguous and finding measures to increase the safety is rather difficult. This is underpinned by the identified input indicators for safety: *Standards compliance* and *complexity*. As can be seen in Figure 4.5 does the *complexity* indicator have a lot of inputs from other indicators. Therefore, in order to better understand complexity of taxiway systems, more research is recommended on this aspect. Nonetheless, several methods for assessing the safety are proposed.

Standards compliance
As one of the two input indicators for safety, the compliance to SARPs is rather important. Analyzing the level of compliance of a taxiway system may expose major vulnerabilities of the taxiway system.

Stakeholder faced problems
Through interviews, stakeholders of the taxiway system can point out faced problems. This might provide important insights, since stakeholders are closely related to the system and face problems while using it.

Occurrence data/black spot
Wilke et al. (2014) suggests analyzing occurrence data for their causal factors. Therefore, occurrences can be mapped through a black spot analysis. Black spots are described as locations that have an extensive number of occurrences (Geurts and Wets, 2003). Next to black spots, also black zones are mentioned in the literature, as arising from the awareness of the evident spatial interaction existing between contiguous accident locations. Geurts and Wets (2003) defines a black zone as a set of contiguous spatial units taken together and characterized by a high number of accidents. Hence, by performing a black spot or black zone analysis, insights can be gained on vulnerable locations within a taxiway system. Besides, in case of limited time, creating a word cloud of occurrence data may provide high level insights on words that are used most often within the occurrences reports (Heimerl et al., 2014). Hence, a word cloud may help to explore important topics in the occurrence reports.

Sustainable safety
In 1992, along with Sweden, a vision on sustainably safe road traffic was firstly conceptualized in The Netherlands. The aim of sustainable safety is achieving safety by systematically reducing underlying risks of the traffic system with a focus on human factors (SWOV, 2018). The awareness that human factors are important when it concerns road safety has been accepted for decades (Hagenzieker et al., 2014; ICAO, 2018b). Already in 1979, Treat et al. stated that people are not only physically vulnerable, but also fallible: they make errors. Therefore, human characteristics are of large importance with concern to safety. Amongst others, also in aviation it has been recognized that rather than adapting people to a system, the system should be adapted to people's abilities and desires, which is also known as 'safety by design' (SWOV, 2018). Sustainable safety comprises all four approaches of airport safety management as identified by ICAO (2018b): the vision is set up on systems level with human factors as thread, and is build up of technical (design) and organizational principles.

To the best knowledge of the author of this thesis, sustainable safety as described by SWOV (2018) has not been applied to taxiway systems before, although taxiway systems show similarities to road systems. Besides, the vision comprises all approaches on safety management as identified by ICAO (2018b), with a focus on humans. Therefore, it is suggested to assess taxiway systems on the five road safety principles of sustainable safety. Below, the five road safety principles are elaborated (SWOV, 2018) and a translation to the taxiway system is made.

Three of the five principles are *design principles*:

1. **Functionality** of roads.

   In accordance with this design principle, a network ideally has a hierarchical and functional structure of traffic functions. In a road network, this structure is built up of three categories of roads:

   - *through-roads* (flow function on road sections and across intersections)
   - *distributor roads* (flow function on road sections and exchange function at intersections)
   - *access roads*[1] (exchange function on road sections and at intersections)

   A similar distinction can be found in taxiway system design with *taxiways*, *apron taxiways* and *aircraft stand taxilanes* (Section 3.3) with each own design criteria (Section 3.5). Besides, SWOV (2018) mentions that in cases where mono-functionality cannot be realized in the short term (referred to as 'grey roads'), efforts should be made to achieve (temporary) results that provide adequate safety by focusing on the most vulnerable user. Based on the interviews, within the taxiway system, flight crews that are unfamiliar with an airport can be seen as vulnerable users.

2. **(Bio)mechanics**: limiting differences in speed, direction, mass and size, and giving road users appropriate protection.

   Fast-flowing traffic should either physically or in time be separated from slow moving traffic, from traffic travelling in opposite direction, from traffic with a substantially different mass or width, and from hazardous obstacles, this second principle implies.

   Within taxiway systems generally no speed limits are defined, those are aircraft or airline specific. Whether opposite directional flows are separated depends on the airport layout: on larger airports directional taxiways may be used

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[1] In Sustainable Safety, an access road is a road for local access. It is not the type of 'access road' that is used in some countries to provide access to a major destination such as a port or an airport, most often a through-road, functionally (SWOV, 2018)

to separate flows, where on other airports separation is solely done by ATC-guidance. Separation of vehicles with substantially different masses can on airport surfaces be seen as separation of aircraft from service vehicles. Service vehicles generally are only allowed on service-roads, and not on taxiways, unless otherwise instructed by ATC. Besides, several airports handle (small) General Aviation (GA) flights in separate areas on the aerodrome. Separation of hazardous obstacles is achieved through clearances (Section 3.5).

3. **Psychologies**: aligning the design of the road traffic environment with road user competencies.

   In accordance to the last design principle, the design of a traffic system is well-aligned with the competencies and expectation of its users. Hence, the information from the traffic system should be perceivable, understandable ("self-explaining"), credible, relevant and feasible. Accordingly, ideally, safe road behaviour is as little as possible dependent on individual users' choices. This is in line with comments of interviewees on complexity (see Section 4.4).

   Transferring information to road users is done by the road layout (in the taxiway system there are no direct differences, only differences in clearances), the road environment (in the taxiway system *aircraft stand taxilanes* are generally located along aircraft stands), traffic signs (visual aids in taxiway systems, see Section 3.5.5) and regulations.

The other two principles are *organization principles*:

4. Effectively allocating **responsibility**. Responsibilities should be allocated and institutionally embedded in such a way that they optimally support maximum road safety as a result for all users. Within the road network, the national government is responsible for the system in the first place, and as such carries the ultimate responsibility with the inherent task to protect its citizens and provide them with the opportunity to transport safely. Since taxiway systems are not necessarily part of the public space, it is questionable whether the national government has the ultimate responsibility for taxiway systems too. Nonetheless, all involved stakeholders should take their responsibility in maximizing safety within taxiway systems.

5. **Learning** and **innovating** in the traffic system.

   In this final principle, SWOV (2018) refers to the Deming cycle: it starts with the development of effective and preventive system innovations based on knowledge of causes of occurrences (*Plan*). By implementing these innovations (*Do*), by monitoring their effectiveness (*Check*) and by making the necessary adjustments (*Act*), system innovation ultimately results in fewer occurrences.

Nevertheless, various barriers are faced in the road system for implementation of the above described principles (Weijermars and Aarts, 2010):

- Lack of stakeholder knowledge about the effectiveness of measures;
- Lack of turning vision into practice;
- Decentralization of policy;
- Opportunities to choose sub-optimal solutions;
- Pressure of other interests;
- Lack of physical space;
- Lack of financial resources.

Similar barriers can be expected within taxiway systems. Therefore, when assessing a taxiway system on the sustainable safety principles, mentioned barriers should be taken into account.
In order to deal with these barriers, the approach of sustainable safety in road traffic systems is implemented in stages, in line with the societal context:

- *Eliminating:* Where possible, dangerous situations are made physically impossible.
- *Minimizing:* The number of dangerous situations are minimized.
- *Mitigating:* Where people unavoidable are exposed to risks, their consequences should be as much as possible be mitigated by taking appropriate mitigating measures.

When defining potential measures for taxiway systems and facing barriers, these stages might be kept in mind.

Ground movement data
Ford et al. (2014) suggest analyzing ground movement data and identifying potentially hazardous interactions between taxiing aircraft, factors that contribute to collision likelihood can be examined. Waldron et al. (2009), Waldron et al. (2013), Ford et al. (2014) and Waldron and Ford (2014) provide extensive suggestions on analyzing potentially hazardous interactions.

Complexity
Next to the standard compliance, complexity is the other input indicator for safety. However, as mentioned in Section 4.4 and shown in Figure 4.5, complexity is a combination of many contributes. Therefore, before being able to assess the complexity of taxiway systems, first further research should be performed on the concept of taxiway system's complexity.

Heat map
Next to the before mentioned analyses, gathering insights on traffic intensities within the taxiway systems is helpful for placing other analyses into perspective. Therefore, a heat map can be developed, mapping traffic demand on either links or nodes within the network. This can either be done based on historical data, or by developing a stochastic model.

4.3 OTHER KEY PERFORMANCE INDICATORS

This section introduces the three other identified KPIs: capacity, robustness and environmental impact. Each of the following subsections introduces one of the KPIs and provides a measurement method for the KPIs. Besides, for each KPI a proposed assessment methods is introduced and direct input indicators are mentioned. These indicators are one or multiple of the identified general indicators. In Section 4.6 the causal relationships are visualized.

4.3.1 Capacity

The planning and management of capacity of airports is widely recognized as important, yet being very challenging (Mirković and Tošić, 2014). According to Eurocontrol (2019), major airports throughout Europe are on the edge of congestion, getting close to saturation, based on their declared capacities. Traditionally, this capacity is often calculated based on the technical characteristics of an airport

(Janić, 2008), whereas Boosten (2017) concludes that throughout the literature no unique definition of airport capacity is provided. Within the literature, lots of different approaches and definitions of airport capacity can be found. For example, Suau-Sanchez et al. (2011) consider total capacity to be an aggregate of infrastructural capacity, airspace capacity and environmental capacity. Based on Suau-Sanchez et al. (2011), Boosten (2017) concludes that many factors determine the airport capacity. These factors can be split up in static (e.g. number of taxiways) and dynamic, of which the latter is related to how airport assets are used and operated within the environmental, economic, socials, and business constraints (Boosten, 2017). Hence, Mota and Boosten (2014) identified airport capacity as a multi-function of multiple factors:

$$\text{Airport capacity} = f(\textit{business model, infrastructure, airspace, societal conditions}) \quad (4.2)$$

Below, the factors as introduced by Mota and Boosten (2014) and Boosten (2017) are elaborated.

Business model: The impact of the business model on the capacity is rather flexible. Examples of inputs for this parameter are the airline business models of airlines operating at the airport, the airport's business model and the relationship between the airport and airlines. The airlines' business models, for example, can have a large impact on the operational capacity of the airport: if only low cost carriers operate at an airport with only Narrow Body aircraft (NaBo), the capacity of the runway can be relatively high since separation distances can be kept small, and turnaround times will be minimized by the airlines. On the other hand, airlines operating a hub-and-spoke network will cause peak hours due to optimizing transfer possibilities for passengers. The relationship is of importance for airport investments, which will indirectly be paid by the airlines through airport fees.

Infrastructure: The infrastructure at the airport is the major inflexible-technical barrier for capacity: the infrastructure defines the maximum capacity limits of what is technically possible within the available assets. Besides, technologies at the airport and on-board of aircraft can impact the technical capacity, for example advanced surveillance technologies can help ground controllers on efficiently guiding aircraft across the airport.

Airspace: The three-dimensional airspace is generally controlled by ATC with support of technologies like radars. Since the monitoring and controlling is performed by humans, there are inherent risks and limits to the control operations.

Societal conditions: The societal parameter is one of the flexible constraints of the maximum airport capacity which does not correspond with the physical limitations of the system. The parameter refers to the impact of stakeholders' interest. This can be either direct or indirect by the government being pushed by society to define limits. Also environmental impacts play a role in this parameter.

Similarly, Bellsola Olba (2018) found that different capacity definitions has been used in the literature for port vessel traffic. Therefore, Bellsola Olba (2018) proposed a new capacity definition for port vessel traffic as "the maximum average vessel flow that can be handled by a port, with its specific infrastructure layout, vessel fleet, traffic composition and demand, satisfying the required safety and service level" (Bellsola Olba, 2018, p. 35). Based on the definitions of Bellsola Olba (2018) and Boosten (2017), a definition for taxiway system capacity is proposed as:

> *"The maximum average vehicle flow, either being a taxiing aircraft or tow movement, that can be handled in an airport taxiway system, with its specific infrastructure layout, aircraft fleet, traffic composition and demand, satisfying the required safety and service level."*

Capacity is considered to be important for the taxiway system as well. ICAO (2005b) states that the capacity of the taxiway system shall never limit the airport capacity. Therefore, the taxiway system's capacity shall at least exceed the capacity of the other airside subsystems of the airport system (Runway system and Apron/Gates). Also de Neufville and Odoni (2013) and the ACI (2019) mention capacity as one of the key factors in airfield design, and thus of the taxiway system. During the interviews, most Airport Representatives mentioned that the capacity of the taxiway system is of large importance, yet hard to measure. Only Operations representative 2 did not mention capacity, indicating that for smaller airports the capacity is of less importance due to lower traffic volumes.

The number and types of runway exits also influences the runway capacity since it influences the runway occupation time. Besides, the interviewees state that the apron capacity of an airport influences the taxiway system's capacity: in case all gates are utilized, aircraft might be directed via holding locations or have to wait on taxiways causing delays (Eurocontrol, 2008). They base this statement on the example that if all gates are occupied, aircraft might have to wait on the taxiway system, limiting the taxiway system's capacity.

Measurement

As mentioned before, Mota and Boosten (2014) define airport capacity as a multi-function. The capacity of taxiway systems can be defined as a multi-function too. During the interviews, interviewees listed several parameters for the capacity of a taxiway system:

- Lengths of links
- Number and complexity of intersections
- The current operation
  - Which runways are in use (determines flow to/from runway)
  - Is there a peak in traffic demand (the demand might fluctuate)
  - Is there a peak on NaBo or Wide Body aircraft (WiBo) (influences the use of runway exits)
  - To/from which aprons are aircraft going (determines flow to/from apron)
  - Conflicting traffic flows

From this list of parameters, similarities with the factors as identified by Mota and Boosten (2014) can be found. The prior two concern the infrastructural capacity, whereas the current operation comprises business model and societal conditions. The airspace does not play a direct role in the capacity of taxiway systems. Hence, the capacity of a taxiway system can be defined as the following multi-function:

$$\text{Taxiway system capacity} = f(\textit{business model, infrastructure, societal conditions}) \tag{4.3}$$

It can be seen that a quantifying method is lacking. Due to time limitations, and since capacity is not a focus KPI in this research, quantification of capacity is not done in this research. Therefore, further research is recommended in order to find a quantifying method for capacity of taxiway systems to support decision making in airport management.

Assessment method

Direct input indicators for capacity are considered to be *complexity, traffic demand* and *quantity of infrastructure*. By relating these to Equation 4.3, complexity and quantity of infrastructure are related to infrastructure and traffic demand is related to both the business model factor and the societal conditions. As mentioned before, further research is needed in order to quantify and analyze the capacity of taxiway systems. However, Yin et al. (2012) mention that most airports face congestion and increased taxi times when the traffic demand at the airport exceeds the capacity. Therefore, evaluating taxi times throughout the past might provide insights on the development of capacity throughout the past, without prior further research.

4.3.2 Robustness

ICAO states that the taxiway system serves to link different aerodrome functions and that it is needed to develop optimum aerodrome utilization. Moreover, ICAO (2005b) states that the taxiway system should minimize the restriction of aircraft movement to and from the runways and apron areas. To achieve this requirement, availability and reliability (robustness) of the taxiway system and continuity of the taxi flow is essential. Interviewees state that for the robustness it is important whether the taxiway system is able to deal with sections (links/nodes) being unavailable, for example due to infrastructural works (e.g. maintenance) or disruptions.

Measurement

Below, a method for measuring robustness is provided, either for a single link or for the complete taxiway system. The measurement method is based on Zhou et al. (2017). The robustness for a link l can be expressed as the average additional taxi distance due to link l being unavailable of each pairs of gates and runways. Zhou et al. (2017) describe a method for measuring robustness against random failure for a set of scenarios. For the taxiway system, the set of scenarios is replaced by the set of links being unavailable. Besides, where Zhou et al. (2017) uses times, the proposed methods uses distance, since for measuring robustness factors like traffic demand should not play a role. It should be noted that the proposed method only takes into consideration the situation in which one link is unavailable, not multiple links being unavailable simultaneously. Besides, nodes are not considered in this model under the assumption that a node being unavailable causes all its connected links to be unavailable.

In case no alternative route is available the $D_{l,g,r}$ becomes infinite.

$$Robustness_l \text{ [-]} = \frac{1}{\exp\left(c_l\right)} \tag{4.4}$$

where

$$c_l = \frac{1}{|G| \cdot |R|} \sum_{g \in G} \sum_{r \in R} (D_{l,g,r} - D_{g,r}) / D_{g,r} \tag{4.5}$$

$$Robustness \text{ [-]} = \frac{1}{|L|} \sum_{l \in L} Robustness_l \tag{4.6}$$

with:
$Robustness_l$ = Robustness of link l
$Robustness$ = Average robustness of the taxiway system
$c_{l,g,r}$ = impact of link l being unavailable
$D_{g,r}$ = initial average taxi distance between gate g and runway r
$D_{l,g,r}$ = average taxi distance between gate g and runway r with link l being unavailable
L = set of links
G = set of gates
R = set of runway (exits/entries)

Assessment method

To assess the robustness of a taxiway system, the above defined measurement method can be executed. By plotting the found robustness values on a map by a colour-scale, the robustness of a taxiway system becomes visible.

Direct input indicators for robustness are *quantity of infrastructure*, *quality of infrastructure* and *flexibility*.

4.3.3 Environmental impact

Nowadays, environmental impact is a core aspect in every project. Most recently, the 'nitrogen crisis' within the Netherlands - which also effects the aviation industry (NOS, 2020) - shows the importance of considering environmental impact of systems. By way of contrast, before 2001, only very little benchmarks with regard to the impact of airport operations on the environment have been performed (Francis et al., 2002). The IATA was the first in taking steps to produce environmental measures for airport operations. The most mentioned indicators for environmental impact are noise and emissions (Andersson Granberg and Munoz, 2013; de Neufville and Odoni, 2013; Graham, 2005). At airports, taxiing aircraft significantly contribute to fuel burn and emissions (Simaiakis and Balakrishnan, 2010). Yet, pilots stated that during taxiing the environmental impact does not play a big role, since they "can decrease the aircraft's emissions much more by making alternative decisions and taking shortcuts during the flight" (Pilot 1). Contrariwise, Remkes et al. (2020) state that within the LTO-cycle[2] taxiing does play a role in declining the environmental impact of airports. In the end, the environmental impact within the taxiway system is considered as one of the KPIs. The environmental impact of the taxiway system in terms of emissions can be considered from two perspectives: potential impact and actual impact.

Measurement

The potential environmental impact can be defined as the efficiency of the system: compared to the bird's-eye distance, what is the average taxi distance between two points in the taxiway system. The potential environmental impact can also be seen as a detour-factor.

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[2] The Landing and takeoff cycle (LTO) includes all aircraft activities that take place below an altitude of 3,000 feet. This includes taxiing before departure, take-off, approaching / landing, taxiing after arrival and idling before and after taxiing (Remkes et al., 2020).

$$\textit{Potential environmental impact}\ [\text{-}] = \frac{1}{|G| \cdot |R|} \sum_{g \in G} \sum_{r \in R} \frac{A_{g,r}}{B_{g,r}} \tag{4.7}$$

with:
$A_{g,r}$ = average taxi distance between gate g and runway r
$B_{g,r}$ = bird's-eye distance between gate g and runway r
G = set of gates
R = set of runway (exits/entries)

The actual environmental impact can be defined as the actual emission of CO_2 and nitrogen per year. The impact is normalized to kilograms per movement, since then the impact of a taxiway system can better be compared with the impact of another taxiway system.

$$\textit{Actual } CO_2 \textit{ impact}\ [\text{kg/movement}] = \frac{\textit{Annual Emission}_{CO_2}}{\textit{Movements per year}} \tag{4.8}$$

$$\textit{Actual nitrogen impact}\ [\text{kg/movement}] = \frac{\textit{Annual Emission}_{nitrogen}}{\textit{Movements per year}} \tag{4.9}$$

Assessment method

In order to assess a taxiway system's environmental impact, both the potential and actual impacts can be measured by the above formulated methods. To gain insights on the meaning of the obtained potential environmental impact values, comparisons should be made amongst airports. For this comparison, it is recommended to use airports within the same development stage (Section 3.4).

Direct input indicators for robustness are *quantity of infrastructure* and *traffic demand*, as can also be distracted from the provided measurement methods.

4.4 ENDOGENOUS INDICATORS

Complexity

In the report of the Dutch Safety Board (2017), it was concluded that the taxiway system at AAS is 'too complex'. Yet, no definition of complexity is provided in the report. Also O'Flynn (2016) mentions complexity of the aerodrome layout as indicator that should be taken into account. Besides, the interviewees indicate complexity as largest contributor to (un)safety. Since there is no definition of complexity of taxiway systems, interviewees were asked what makes the taxiway system complex from their point of view.

Below an overview is provided of answers given by the interviewees. Between brackets the contributing indicator is mentioned.

The taxiway system becomes...

- *more complex if there is much infrastructure* [Quantity of Infrastructure]
    - Large surfaces of concrete make identifying routes difficult
    - Many parallel taxiways make situational awareness more difficult

- *more complex if there are many decision points* [Quantity of Infrastructure]
    - Especially if decision points are close to each other
    - The number of options on one decision point
    - If options have different purposes (e.g. taxiway or runway entry)
- *less complex if the infrastructure is clear, well-arranged and logical* [Quality of Infrastructure]
    - It should be interpretable in only one way (self-explaining)
    - Preventing independent decisions
    - Uniformity (equal measures for equal situations)
    - Clear and logical designations of taxiways
    - As less as possible conflicting traffic / flows [Dependency]
    - Prevent dependencies within the system [Dependency]
- *more complex with more hot spots* [Quality of Infrastructure]
- *less complex with good ATC* [Quality of Procedures]
    - Preventing long taxi instructions
    - Preventing regularly deviations from standard procedures
    - Proper English communication
- *less complex with proper visual aids* [Quality of Infrastructure]
    - Increasing situational awareness
- *less complex if the situation is predictable* [Quality of Procedures]
    - Irregularities increases the risk of mistakes
    - The frequency of changes is usage of the taxiway system
- *less complex with proper preparation of the Flight Crew* [Quality of Procedures]
    - Predict taxi route and discuss during approach briefing
    - Study the airport's ground movement chart and keep it while taxiing
    - Easier for flight crews that visit an airport regularly
    - Easier for flight crews that are more familiar with the airport's procedures

Besides, interviewees state that complexity is hard to quantify, since it is the combination of many contributes - as can be seen on the long list of different answers - and that the complexity depends on the perspective (e.g. a pilot based on the airport or a pilot visiting the airport for the first time, or a representative of the airport's Asset Management department).

Nonetheless, Bonchev and Buck (2005) discuss several methodologies for quantifying the infrastructural complexity of networks. Since the taxiway system can be seen as a network as well, these methodologies might be applicable for taxiway systems too.

For a network defined by a set of V *Vertices* (nodes), $\{V\} \equiv \{v_1, v_2, ..., v_v\}$, and a set of E *Edges* (links), $\{E\} \equiv \{E_1, E_2, ..., E_E\}$, the edge $\{ij\}$ is the line that emanates from vertex i and ends at vertex j. Bonchev and Buck (2005) quantify complexity by the information content of the vertex degree distribution of a graph, I_{vd}:

$$I_{vd} = \sum_{i=1}^{V} a_i \log_2 a_i \qquad (4.10)$$

with a_i the adjacency of vertex i (number of edges connected to a vertex).

Nonetheless, next to infrastructural complexity, also operational complexity plays an important role. However, no method for quantifying the total (infrastructural and operational) complexity has been developed in the literature yet.

As mentioned before, complexity is considered as the largest contributor the (un)-safety. Hence, interviewees expect less safety within the taxiway system, as it becomes more complex. Besides, higher complexity can decrease the capacity.

Availability

The availability can also be defined as opposite of failure susceptibility - or the chance on failures within the taxiway system. More failures may lead to more disruptions and thus less availability. For both availability and robustness, a maintenance strategy might be helpful.

Dependency

The dependency can be seen in two ways: an aircraft (flight crew) dependent of another aircraft, and/or an aircraft (flight crew) dependent of the infrastructure.

In the first case, dependency can occur if a single taxiway should be used for two-way traffic (one of the aircraft will have to wait till the other has left the single taxiway) or if on a parallel taxiway a limit to wingspan is defined in case an aircraft of a certain wingspan taxis on the other taxiway (e.g. an code F on a taxiway limiting the parallel taxiway to code C, meaning that aircraft >code C will have to wait). Also the number of intersections can make the dependency greater, since only a single aircraft can use an intersection at a time. The dependency of aircraft to each other was underpinned by Operations representative 1 by mentioning that the change of one flight's Target Off-Block Time (TOBT) at AAS currently impacts the Target Start-up Approval Time (TSAT) of nine other flights.

In the latter case, it depends on the infrastructure whether an aircraft can use the infrastructure or not due to limitations. On many airports this dependency is applicable for smaller taxiways, where limitations to the wingspan of the aircraft are applied.

Based on the interviews, dependency can be seen as a contributor for complexity: more dependency leads to higher complexity.

Flexibility

The flexibility has different forms: the flexibility of the taxiway system in relation to...

- the possible types of aircraft it can accommodate;
- alternative routings over the surface movement area;

The flexibility in possible aircraft types is linked to dependency: the less possibilities, the more dependent and vice versa. Flexible routings are a major desire of ATCOs. It enables them to make use of more routing alternatives for aircraft, as stated by all Airport Operator Representatives. Hence, higher flexibility leads to higher robustness of the taxiway system.

4.5 EXOGENOUS INDICATORS

Standards compliance

As mentioned before, ICAO defined Standards and Recommended Practices (SARPs) on taxiway Design and planning. All SARPs are intended to contribute to safe operations (ICAO, 2005b). Also most of the interviewees, including all Airport representatives (operations and asset management) and airport consultants, underpin the importance of compliance to the standards. Hence, it can be concluded that the level of compliance to these standards influences the level of safety: a higher level of compliance intends a higher level of safety.

Traffic demand

The interviewees state that the traffic demand and traffic flow on the taxiway system - as a result of the traffic demand of the airport - is of large importance when assessing an airport.

The traffic flows influence the complexity: pilots state that busier airports feel more complex. They declare this partly by means of higher dependency of other aircraft (conflicting flows), and partly by means of distraction due to more radio communication between flight crews and ATC. More conflicting flows also decrease the capacity of the taxiway system, especially the capacity of intersections, interviewees expect. Without using new technologies or more environmental friendly aircraft, the environmental impact increases with increased traffic demands.

Quality of procedures

Next to the infrastructure, the procedures are of large importance for the usage of the taxiway system. The interviewed Airport Planner stated that always a consideration should be made between adjusting/adding infrastructure and/or adjusting the procedures, since through good usage of procedures a lot is possible. The quality of procedures can be found in the quality of ATC, predictability within the operation and preparation of the flight crew.

Good procedures can contribute to flexibility, decrease dependency and make the usage of the taxiway system less complex.

Quantity of infrastructure

The quantity of infrastructure on the airport influences many other parameters. Based on the given answers during the interviews, the following measures for quantifying the infrastructure were identified:

- Number of nodes
- Number of links
- Number of links per node
- Distance between nodes

These measures can be translated to well-known network indicators (Bonchev and Buck, 2005; Cats, 2018):

- Number of vertices (nodes) V
- Number of edges (links) E
- Connectivity - the share of edges out of maximum number of edges possible

  $$\gamma = \frac{|E|}{|V|^2 - |V|} \tag{4.11}$$

- Network adjacency

  $$A = \sum_{i=1}^{V} = a_i \tag{4.12}$$

  where a_i is the adjacency of vertex (node) i

- Average vertex degree - average number of links per node

$$< a_i >= \frac{A}{V} \tag{4.13}$$

An increase in V or E not necessarily increases the complexity, since the I_{vd} (see Equation 4.10) depends on the number of links per node. Hence, an increase in Network adjacency is expected to increase the complexity. However, this is not the case with a large share of vertices with only one edge; these do not contribute to complexity of the network, according to Equation 4.10.

Besides, an increase in average vertex degree increases the dependency. An increase in connectivity increases the capacity, robustness and flexibility. Contrary, an increase in the number of vertices and number of edges increases the environmental impact and decreases the availability.

Quality of infrastructure

The operational quality of infrastructure mainly is primarily based on:

- Clearness and logic of the taxiway system;
- Number of hot spots;
- Quality of visual aids.

Good quality of infrastructure contributes to robustness and availability of the taxiway system. Besides, increasing quality might decrease the complexity. However, since quality of infrastructure is hard to measure, determining its contribution to complexity is difficult too.

4.6 CONCLUSION

Based on literature and interviews, 13 indicators for assessing taxiway systems were identified in this chapter, including four KPIs: safety, capacity, robustness and environmental impact. The KPIs are elaborated in Section 4.3. For each of the KPIs a measuring method is defined, as well as an assessment method. Through assessing taxiway systems on these KPIs, subjects that need more work to be improved can be found. However, a quantification of capacity turns out the be rather difficult due to the large number of parameters. Hence, no quantitative measurement method for capacity of the taxiway system has been defined yet.

In general, responses of the interviewees from the same group (pilots, airport operations, etc.) are in line with each other. Nevertheless, a number of things stand out:

- Asset Manager 4 and Operations representative 2, both representatives of small airports (Maastricht Aachen Airport (MAA) and Groningen Airport Eelde (GAE)) did not mention *capacity* and *complexity* as indicators, whereas all AAS representatives did. This suggests that both capacity and complexity do not play an important role for smaller airports due to lower traffic volumes and smaller aerodromes (lower infrastructural complexity). Moreover, the representatives of smaller airports did not mention the operational quality of the taxiway system as an indicator.
- None of the pilots considered capacity as indicator for taxiway systems. This suggests that they do not think about the capacity of taxiway systems and expect it to be sufficient at all times.

- None of the interviewees mentioned environmental impact to be important. Contrary, Pilot 1 states environmental impact to be unimportant for the taxiway system, since he expects to be able to do more against environmental impact during the en-route flight phase. Nonetheless, environmental impact is considered as one of the KPIs due to societal importance of the impact.

The in this chapter identified indicators and Key Performance Indicators (KPIs) have causal relationships. Throughout the chapter, causal relations are described for the outgoing arrows. The causal relations are shown in causal relation diagram in Figure 4.5.

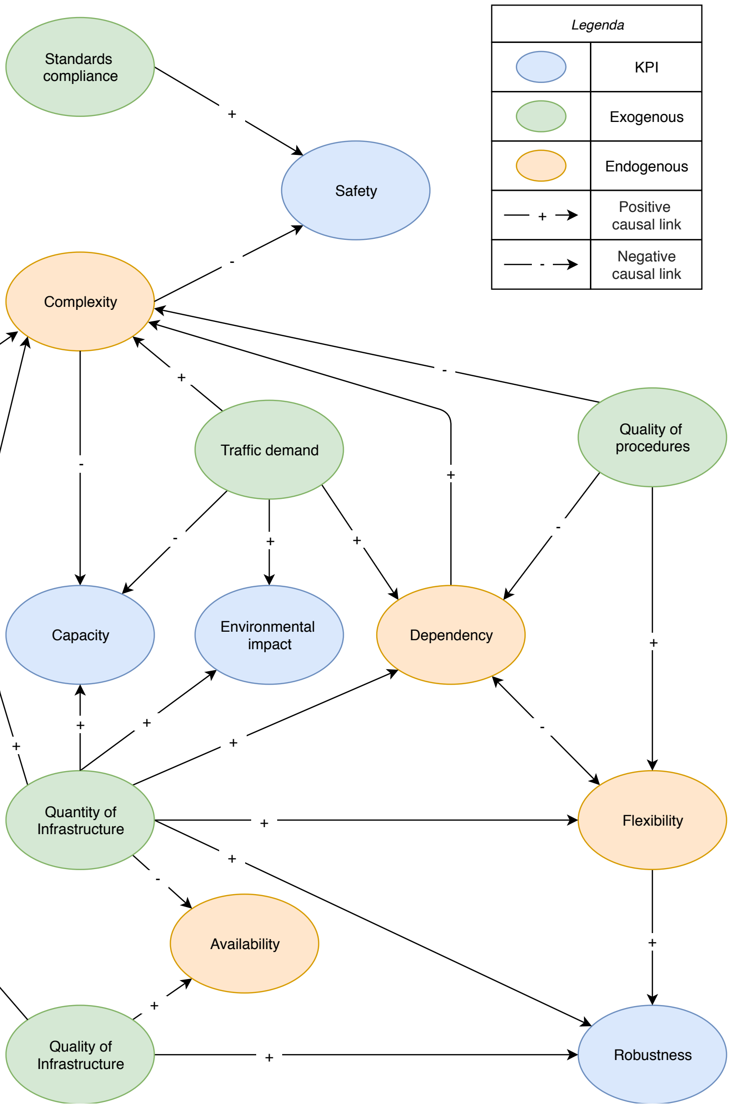


Figure 4.5: Causal Relation Diagram of the indicators and KPIs

By defining KPIs for taxiway systems, the second objective of this research is achieved and Sub Questions (SQs) 4 and 5 are answered. The in this chapter provided definition and assessment methods for the safety KPI will be used in Chapter 6 to assess the safety within the taxiway system of AAS.

5 EXPLORING AMSTERDAM AIRPORT SCHIPHOL

This chapter provides an introduction to Amsterdam Airport Schiphol (AAS). First, Section 5.1 elaborates on the history of the airport. Second, in Section 5.2 insights on traffic demand at AAS are provided. Third, Section 5.3 describes different aspects of the the usage of AAS. Fourth, Section 5.4 elaborates on the characteristics of the taxiway system at AAS and the used procedures. Fifth, the processes within the taxiway system are described in Section 5.5. In the end, a stakeholder analysis for the taxiway System at AAS is performed in Section 5.6. Information in this chapter is based on literature research and interviews with interviewees associated with AAS. Besides, observations of Flightradar24 and live Air Traffic Control (ATC) Ground and Tower frequencies (LiveATC) are used.

5.1 FROM POLDER TO INTERCONTINENTAL HUB

Amsterdam Airport Schiphol (AAS) started over 100 years ago, in 1916, at a piece of land in the Haarlemmermeer polder which was bought from a farmer by the Dutch military (Schiphol, 2019j). After the First World War, the first civilian flights started at Schiphol and the Royal Dutch Airlines (KLM) was founded in 1919. As the airport became property of the municipality of Amsterdam, the airport was developed at high speed: a concrete apron was built, as well as a new terminal building. During the Second World War, AAS was attacked by the Germans and the airport became a base for the German Air Force. After the Second World War, Schiphol was completely destroyed. However, the airport was rebuild in a few months and already in July 1945 the first passenger flights arrived again on AAS.

Figure 5.1: Jan Dellaert presenting his master plan (Schiphol, 2019j)

In 1949, airport manager Jan Dellaert presented his plans for expansions of AAS. His plan (see Figure 5.1) was based on a tangential runway systems with a central traffic area. This model enables the airport to operate at maximum capacity, regardless of the wind direction, with six to eight runways (Techniek in Nederland, 2010). The tangential design requires extensive use of space. The master plan was partly based on the fear that in the longer term AAS would not be a natural destination for

European airlines, unless the airport would be able to attract traffic by offering high quality services. Another opportunity was using the airport for transfer passengers. Therefore, potential growth of the airport was of large importance in the plan. The relatively large and empty polder in which the airport was located enabled for the tangential design.

Dellaert's master plan for AAS formed the basis for the airport as it is known nowadays. After his presentation, Schiphol and KLM further elaborated the plan and consulted Netherlands Airports Consultants (NACO) for remarks on the plan (Van Wageningen, 1953). The elaborated master plan was based on 100,000 annual movements and 2 million passengers around the 1970s/1980s (Schiphol, 1953). As AAS was proposed to become a center in the European and Intercontinental air traffic, the aim was to have the airport meet the highest requirements (NACO, 1953). In general, safety was the most important criterion for assessing the design, followed by capacity. For the airside infrastructure, next to the general criteria, important criteria were taxi distances between the runways and terminal areas, and nuisance for neighbours. Nonetheless, NACO (1953) recognized that amongst the objectives of the design, contradictions were present. Consequently, they concluded that the most satisfying design would be a compromise at all times. Besides, NACO concluded that, despite the fact that the proposed tangential system might suggest a high capacity due to the large number of runways, the capacity is restricted to specific meteorological conditions (Van Wageningen, 1953).

In the end, the renewed AAS as opened in 1967 became smaller than planned by Dellaert, but the main thoughts remained. In the final design, the airport consisted of five (renewed) runways in a tangential system with a maximum length of 3,000 meters, surrounding a central area. At the moment of the opening (see Figure 5.2a), the airport consisted of four runways: *Oostbaan* (opened in 1938), *Aalsmeerbaan* (opened in 1950, but in line of the plan extended in 1961), *Kaagbaan* (opened in 1960,), and *Amstelveenbaan* (opened in 1961, nowadays known as *Buitenveldertbaan*). One year later, in 1968, the fifth runway as mentioned in the plan was opened: the *Zwanenburgbaan*.

(a) AAS in 1966 **(b)** AAS in 1989

Figure 5.2: Development of AAS between 1966 and 1988 (Schiphol, 2019j)

In the meanwhile jet engines were introduced and in 1971 KLM was the first European airline using the Boeing 747. In 1975, AAS opened a second terminal building and the D-pier was opened to facilitate the jumbo jets. In the next decade, the hub-and-spoke-concept became more and more the standard and AAS became one of the largest European hubs. In 1989, a new master plan for 2003 was published. Besides, the Dutch Government designated AAS as 'mainport': an international hub for air-, road-, and rail-connections and a key factor in the Dutch economy. A new ATC tower was opened in 1991, as planned in the 1988 master plan. The new tower was needed to ensure a good view on the expanded aprons, taxiways and runways for the Air Traffic Controllers (ATCOs). In 2003 the (newest) sixth runway was opened: the *Polderbaan*. The runway was constructed to enable ATCOs to let the air traffic fly over less densely populated areas as much as possible.

Nowadays, the airport is still developing. For AAS, the ambition is to further develop the airport in a sustainable way to become Europe's Preferred Airport: the preferred airport for passengers, airlines and logistics service providers (Schiphol, 2019c). In order to be able to accommodate the growing number of passengers and growing number of aircraft, the airport is expanding. Within the central area the new A-pier is being build and in the Northern area the Uniform-apron is being extended in order to increase the capacity of aircraft parking positions. In Appendix F, the AAS 'Basiskaart' and Ground Movement Chart are attached.

5.2 TRAFFIC DEMAND

As mentioned in Chapter 1, the Air Transportation System (ATS) has been growing almost ceaselessly for the past decades, and so has AAS. Figure 5.3 shows that since 1992, both the number of passengers and the number of movements only decreased twice: firstly after the 9/11 attacks in the United States and secondly during the economic crisis of 2007-2009. The figure also clearly shows the (almost) reached limit of 500,000 annual movements at AAS. Nonetheless, the past years the number of passengers have been growing, due to increased usage of larger aircraft (Luchtvaartnieuws, 2018).

In 2019, AAS handled a record of 71,706,999 passengers, 3.5 times the number of passengers in 1992 (19 million). These passengers were handled through 496,826 movements, slightly less than the number of movements in 2018 (499,444), but still over twice the number of movements in 1992 (238,812).

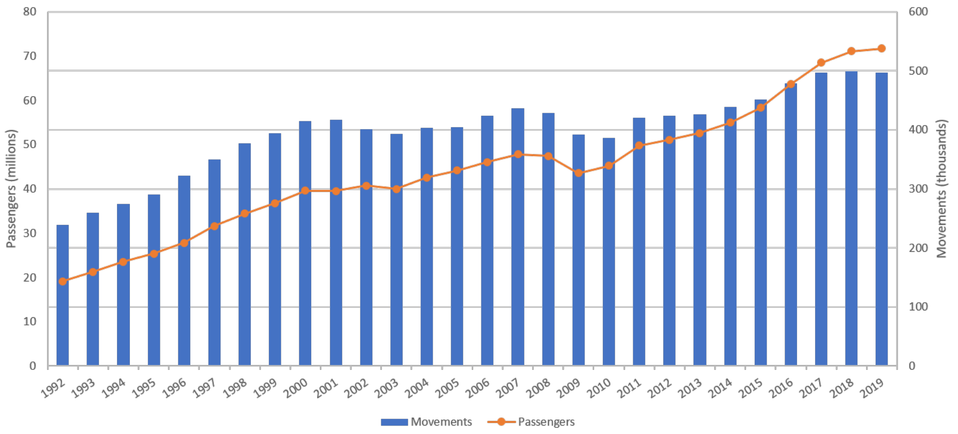


Figure 5.3: Growth of passengers and movements at AAS (Royal Schiphol Group, 2019b)

Zooming in on the monthly number of movements op the past decade (Figure 5.4), the effect of the summer and winter schedule/season becomes clearly visible: peaks in traffic demand can be found during the summer schedule, where during the winter schedule the traffic demand drops down. The summer schedule is effective from the last Sunday of March until last Sunday of October, and the winter schedule is effective from the last Sunday of October until last Sunday of March (Schiphol, 2019f).

5.3 OPERATIONAL CONCEPT OF THE AIRPORT

As mentioned in Chapter 3, the main purpose of taxiway systems is enabling traffic to taxi between runways and aprons (and vise versa). Therefore, in order to understand the usage of taxiway systems at AAS, this sections starts with elaborating on the hub-function AAS holds. Next, the usage of runways is discussed, followed

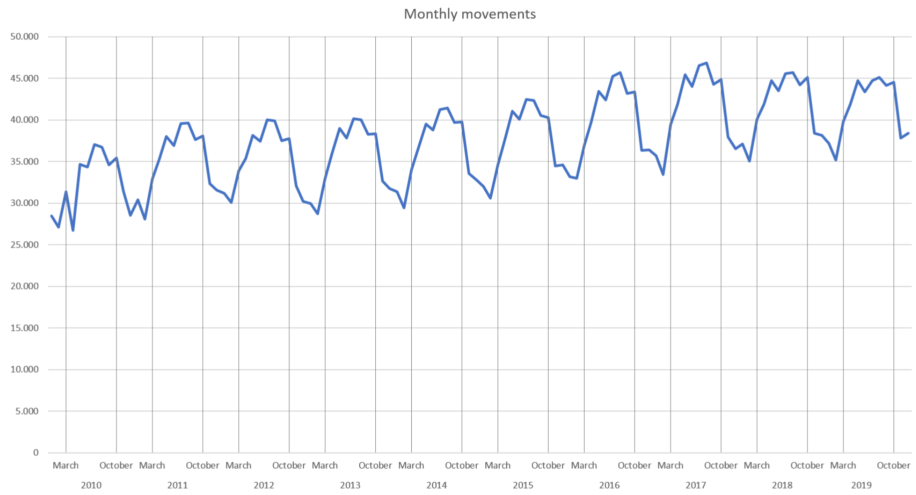


Figure 5.4: Overview of monthly movements at AAS (Royal Schiphol Group, 2019b)

by the usage of aprons and gates. Since AAS is a Collaborative Decision Making (CDM)-airport, and interviewees state that this influences the taxiway system, Airport Collaborative Decision Making (A-CDM) and how it is being used at AAS is discussed as well. Afterwards, the usage of the taxiway system at AAS is discussed in Section 5.4 and the corresponding processes in Section 5.5.

5.3.1 Hub-function

As was already forecast by Jan Dellaert in its master plan (see Section 5.1), transfer passengers are of large importance for AAS. In 2018, 36.6% of the passengers at AAS were transfer passengers (Royal Schiphol Group, 2019a). These transfer passengers are the result of AAS's hub-function for KLM and its codeshare-partners (primarily SkyTeam-partners like Air France and Delta Airlines); The airport is the central point in the hub-and-spoke-network of airports for these airlines. With 49.5% of the annual movements and 48.3% of the annual passengers at AAS, KLM is the airport's major airline (Royal Schiphol Group, 2019a). Worldwide, AAS was second - behind Frankfurt Airport - in the number of transfer-connections per week (hub-connectivity) in 2018 (Royal Schiphol Group, 2019a).

In order to optimize transfer opportunities, KLM started using inbound and outbound waves at AAS in the 1990's (Cornelisse, 2016). The general principle of the wave-operation is sequentially arrival of intercontinental flights, arrival of European flights, departure of European flights, and finally departure of intercontinental flights per wave. As shown in Figure 5.5, currently KLM operates seven major waves at AAS.

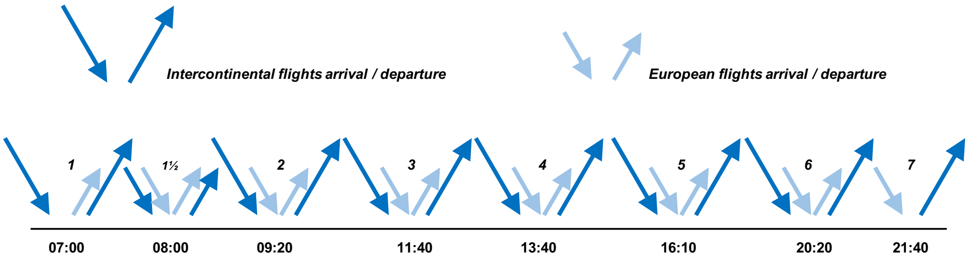


Figure 5.5: KLM's in- and outbound peaks at AAS (adapted from BAS (2019b) and Cornelisse (2016))

5.3.2 Runways

As mentioned in Section 5.1, AAS currently has six operable runways (see the overview in Table 5.1 and Figure 5.6). As owner of the assets, AAS makes the airside infrastructure available to Air Traffic Control the Netherlands (LVNL), whos ATCOs assign infrastructure to flights (pilots) and guide them. The number of runways that are used simultaneously mainly depends on the traffic demand. Which runways are used mainly depends on the meteorological conditions (e.g. wind direction and speed, cloud basis, rain), environmental rules and restrictions and eventual unavailability of a certain runway due to disruptions. Besides, AAS is restricted by regulations in which is stated which runways may be used in which direction during day (06:00-23:00) and night (23:00-06:00). As can be seen in Figure 5.7, runways 36L and 18L may never be used for landings and takeoffs are never allowed from runways 18R and 36R. During day time (Figure 5.7a), no further permanent restrictions are applicable. During night time, more runways shall not be used, as well as several runways that only may be used if the preferred runways are not available (see Figure 5.7b).

Runway designation	*Runway name*	*Dimensions [m]*	*Constructed [year]*
04 / 22	Oostbaan	2020 x 45	1938
06 / 24	Kaagbaan	3439 x 45	1960
09 / 27	Buitenveldertbaan	3453 x 45	1961
18L / 36R	Aalsmeerbaan	3400 x 45	1950
18C / 36C	Zwanenburgbaan	3300 x 45	1968
18R / 36L	Polderbaan	3800 x 60	2003

Table 5.1: Overview of runways at AAS (AIP The Netherlands, 2019)

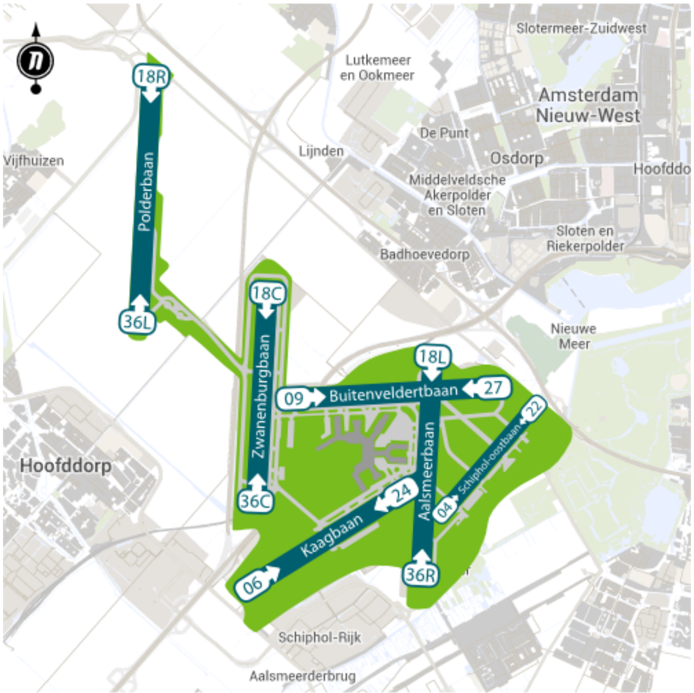
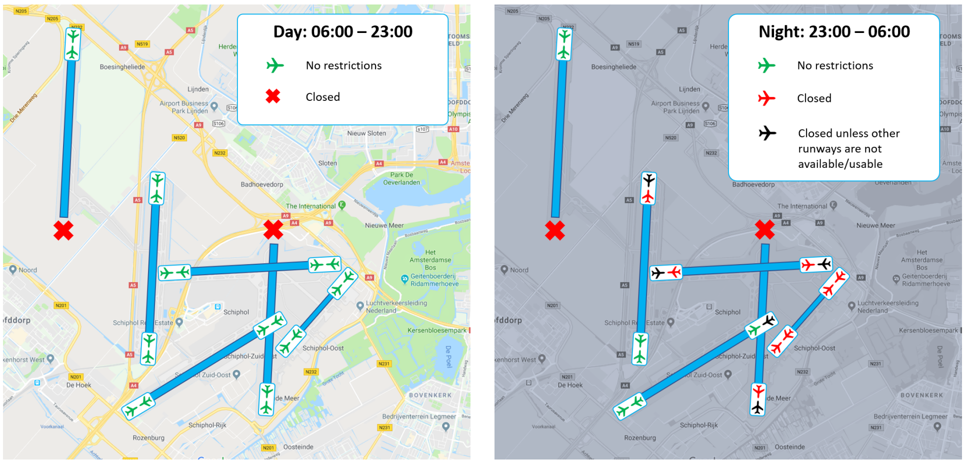


Figure 5.6: Current runway configuration at AAS (BAS, 2019b)

Since KLM - together with its partners - is accountable for over 50% of the aircraft movements at AAS, their schedule has a large influence on the operational conditions at the airport. The previously described seven waves (Figure 5.5) result in inbound and outbound peaks. During these peaks, sometimes AAS has to accommodate 100 flights per hour (BAS, 2019b). In order to accommodate these flights, under normal

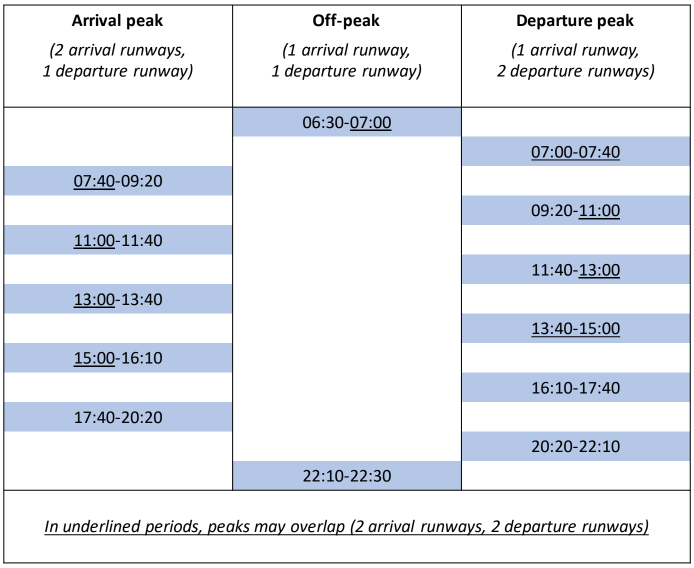


(a) Day time operations **(b)** Night time operations

Figure 5.7: Allowed usage of runways at AAS for periods of time (BAS, 2019b)

conditions three runways are used simultaneously during day time, called "2+1". During outbound peaks, two runways are used for takeoffs and one runway for landings ("2+1"). During inbound peaks, two runways are used for landings and one runway for takeoffs. Throughout the day, the inbound peaks and outbound peaks alternate. In practice, there might be some overlap as well. On these moments, it is allowed to use four runways simultaneously: two for takeoffs and two for landings ("2+2"). Yet, this operation has been restricted by introducing the 'fourth-runway-rule' (Verstraeten et al., 2018), in order to limit the number of aircraft movements on a fourth runway to 80 aircraft movements per day, and to an annual average of 40 aircraft movements per day. When there is no peak (off-peak, including night-time), one runway for takeoffs and one runway for landings will be used ("1+1"). Hence, under normal conditions, AAS never uses only a single runway in segregated mode (runway used for both landings and takeoffs simultaneously).

Based on the Summer 2019 schedule of AAS, BAS (2019b) developed an indicative overview of the inbound and outbound peaks throughout the day for this period (Table 5.2). The exact times on which certain runway configurations are used depend on actual circumstances.



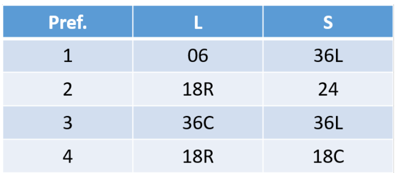
Arrival peak *(2 arrival runways, 1 departure runway)*	**Off-peak** *(1 arrival runway, 1 departure runway)*	**Departure peak** *(1 arrival runway, 2 departure runways)*
	06:30-07:00	
		07:00-07:40
07:40-09:20		
		09:20-11:00
11:00-11:40		
		11:40-13:00
13:00-13:40		
		13:40-15:00
15:00-16:10		
		16:10-17:40
17:40-20:20		
		20:20-22:10
	22:10-22:30	
In underlined periods, peaks may overlap (2 arrival runways, 2 departure runways)		

Table 5.2: In- and outbound traffic peaks at AAS (based on BAS (2019b))

For the choice which runways are used (the runway configuration), first runways that are under maintenance are excluded, as well as runways that do not comply due to meteorological conditions: too much cross wind or tail wind and sight conditions (Verstraeten et al., 2018). Next, preferential runway configurations are used. These preferential configurations are developed through the 'Alderstafel'[1] in order to minimize noise hindrance and are applicable since the Alderstafel advise of October 8, 2013 (Alders, 2013). The included runways in each preferred configuration also comply with the permitted uses per day and night as shown in Figure 5.7. The sequence of preferential combinations is defined within the requirements for safe handling with a sufficient (peak) hour capacity. Each runway configuration exists of four runways, with a distinction made within the configuration between a primary and secondary takeoff (start) runway (designated as S1 and S2, respectively) and a primary and secondary landing runway (designated as L1 and L2, respectively). The preferential runway configurations for day time operations (Table 5.3) and night time operations (Table 5.4) are shown below.

Sight	Pref.	L1	L2	S1	S2
"good" sight = 5,000m AND cloud base = 1000ft AND with daylight	1	06	(36R)	36L	(36C)
	2	18R	(18C)	24	(18L)
	3	06	(36R)	09	(36L)
	4	27	(18R)	24	(18L)
"good or marginal" sight > 1,500m AND cloud base > 300ft	5	36R	(36C)	36L	(36C/09)
	6	18R	(18C)	18L	(18C/24)

Table 5.3: Preferential runway configurations during day (06:00-23:00) (Alders, 2010)



Pref.	L	S
1	06	36L
2	18R	24
3	36C	36L
4	18R	18C

Table 5.4: Preferential runway configurations during night (23:00-06:00) (Alders, 2010)

In the preferential runway configurations, it can be seen that the Oostbaan (04/22) is not used. Nonetheless, under severe weather circumstances with strong winds from the South-West, runway 22 is might be used for landings. Besides, the Oostbaan is primarily used for handling General Aviation (GA).

5.3.3 Aprons

Multiple types of aprons are used at AAS. The airport distinguishes eight stand types, as shown in Figure 5.8, based on the available equipment on the stand and the possible activities with the present equipment. There is an upward hierarchy for types F - A with regard to the level of equipment and allowed activities (Prent, 2019). On type F stands only parking of aircraft is permitted and there is no equipment present. Type E stands are similar to type F, but also catering of the aircraft and fuelling is allowed. On stand types D, C, B and A also passenger and freight handling is allowed. Stand types D and C are both intended for remote handling of passengers. Hence, passengers are transported to the aircraft by bus. Differences between the types can be found in the equipment: type C stands are equipped with fuel hydrants, Visual Docking Guidance System (VDGS) and shore

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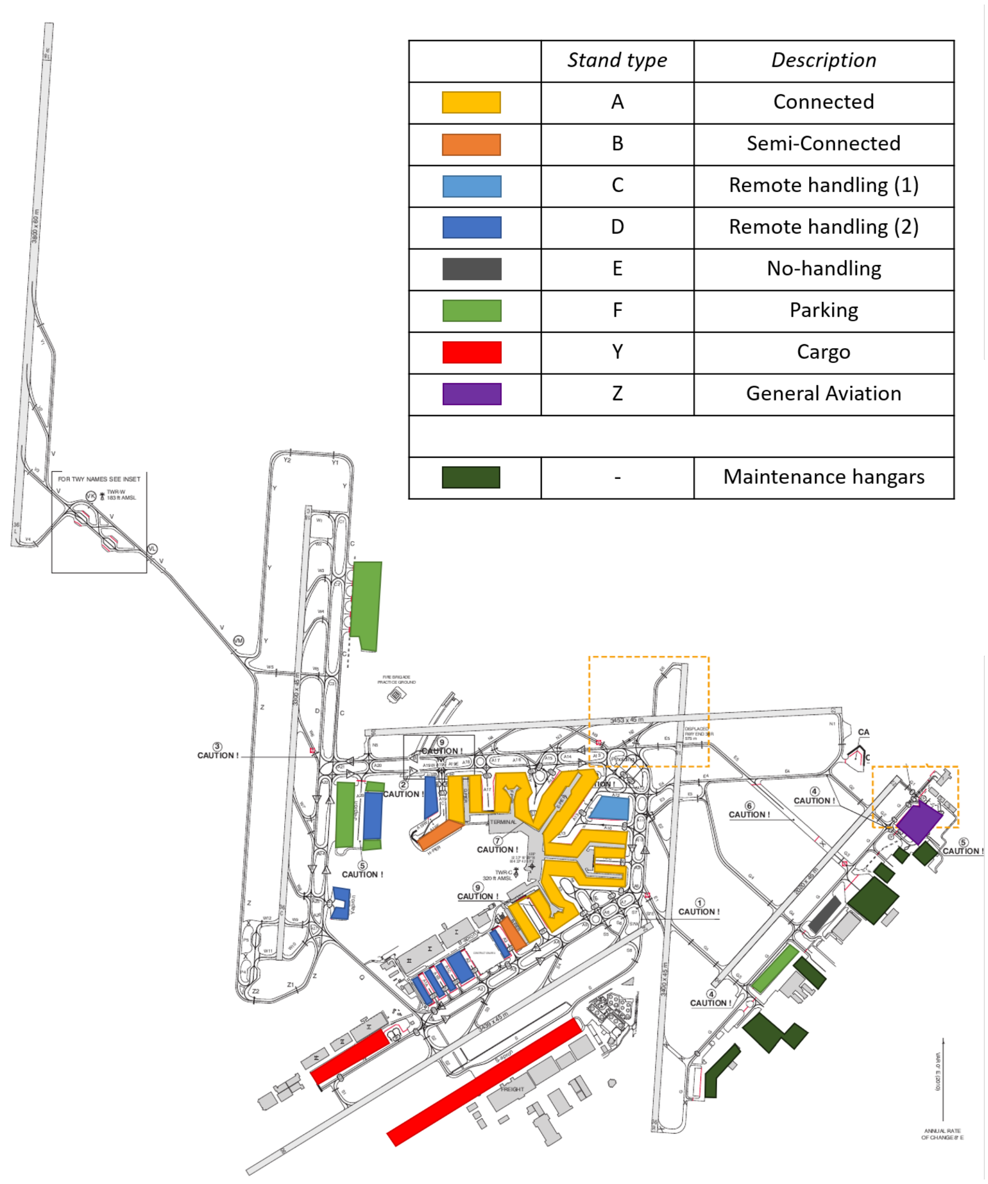
[1] The 'Alterstafel' (table of Alders) is a consultative body in which the government, the aviation industry and residents discuss the development of aviation in The Netherlands and the influence on the surroundings under supervision of former minister Hans Alders.



	Stand type	*Description*
🟨	A	Connected
🟧	B	Semi-Connected
🟦	C	Remote handling (1)
🟦	D	Remote handling (2)
⬛	E	No-handling
🟩	F	Parking
🟥	Y	Cargo
🟪	Z	General Aviation
🟩	-	Maintenance hangars

Figure 5.8: Different apron types and maintenance facilities located at AAS (based on Schiphol (2019d) and AIP The Netherlands (2019))

power, where aircraft on stand type D are fuelled by trucks, guided by marshals, and Ground Power Units (GPUs) are used. Stand types B and A are fully equipped. On type B stands, passengers board the aircraft via a stairs, but since the stand is located in front of the pier, passengers do not need to be transported to the aircraft by bus. At AAS this is called 'semi-connected'. Type A stands are equipped with Passenger Boarding Bridges, allowing passengers to board the aircraft directly from the pier. Stands of type Y, meant for cargo flights, are located in the Southern area of AAS, next to the Kaagbaan: the *Romeo* (R)-apron and the *Sierra* (S)-apron. General Aviation (type Z) is handled at the General Aviation *Kilo* (K)-apron in the North-East of AAS.

The stands for handling passenger flights (types A-D) are located around the terminal building. In general, there are five typical terminal configurations: linear, finger pier, satellite, midfield and transporter (ICAO, 2018a). At AAS mainly piers, with a row of aircraft gate positions on both sides and a passenger concourse along the axis, are used. Piers can have many shapes, but often they are Y-, T-, or I-shaped (de Neufville and Odoni, 2013). Since taxilanes between piers are blind alleys, the capacity may be affected. Therefore, Horonjeff et al. (2010) advises to use two taxilanes between two piers with many aircraft movements.

The terminal area of AAS consists of seven piers, of which four are I-shaped and three are Y-shaped, see Figure 5.9. The figure also shows which piers are used for Schengen, Non-Schengen or Mixed operations. Also the A-apron is shown, since the majority of KLM Cityhopper flights are handled there following the transporter principle (transport of passengers by bus from the terminal to the aircraft and vice versa). On the B-, C-, and H/M- pier, only Narrow Body aircraft (NaBo) aircraft are handled, on the D-pier a mixture of NaBo and Wide Body aircraft (WiBo) aircraft is handled, where on the E-, F- and G-pier primarily WiBo aircraft are handled.

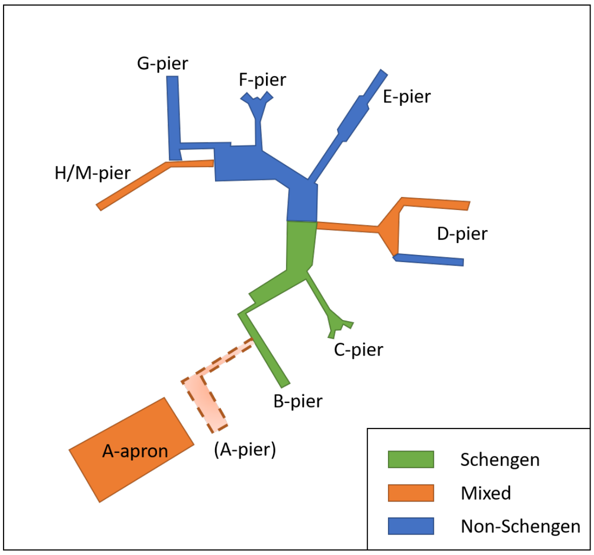


Figure 5.9: Piers at AAS

Stand allocation

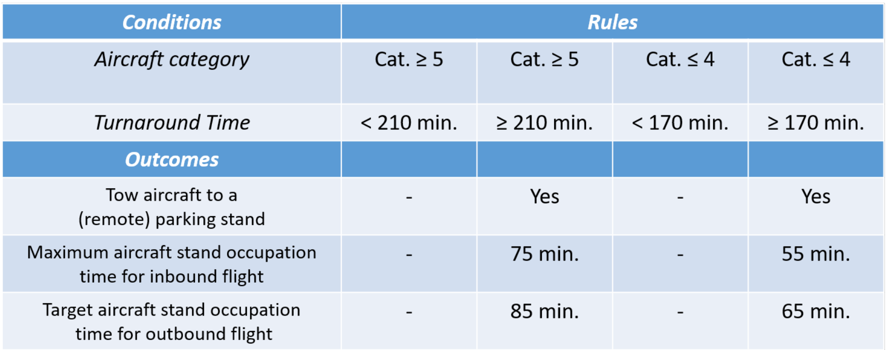
Although all stands of types A, B, C, and D are able to handle passenger flights, not each flight can be assigned to each stand/gate. At AAS the 'Regulation Aircraft Stand Allocation Schiphol' is used for flight-to-stand allocation. The allocation process is subject to two major restrictions (Schiphol, 2019f):

Firstly, the border status zones. Based on agreements between the Dutch State and foreign governmental authorities concerning the free movement of goods and persons, the terminal of AAS has been divided in zones. The zones distinguish Schengen passengers (these passengers are exempt from border control when travelling between Schengen countries) and non-Schengen passengers (see Figure 5.9). In addition, there is a distinction between passengers from screened or unscreened airports/countries: only piers E, F and G can handle unscreened Non-Schengen passengers.

Secondly, the allocation is subject to physical restrictions: mainly related to dimensions. AAS has aircraft stands of different dimensions, split up in categories (1 - 10). These categories are based on the dimensions of aircraft types (see Section 5.4).

Intermediate parking

As explained in Section 3.2.2, in some cases aircraft are parked at a (remote) parking stand in-between the arrival- and the departure process. At AAS capacity is the major reason for intermediate parking. The decision on whether a flight is intermediate parked is time based. As soon as the departure stand is available, the aircraft will be towed to the departure stand to begin the departure process on time. The norms used at AAS for turnaround time and handling times in the decision to tow an aircraft to a (remote) parking stand are showed in Table 5.5. The norm for a towing procedure is 10 minutes and the airport aims at a minimum time at the (remote) parking stand of 30 minutes (Schiphol, 2019f).



Conditions	*Rules*			
Aircraft category	Cat. ≥ 5	Cat. ≥ 5	Cat. ≤ 4	Cat. ≤ 4
Turnaround Time	< 210 min.	≥ 210 min.	< 170 min.	≥ 170 min.
Outcomes				
Tow aircraft to a (remote) parking stand	-	Yes	-	Yes
Maximum aircraft stand occupation time for inbound flight	-	75 min.	-	55 min.
Target aircraft stand occupation time for outbound flight	-	85 min.	-	65 min.

Table 5.5: Norms for relocation at AAS *(Dutch: afsleepnorm)*

5.3.4 A-CDM

Since May 2018, AAS is a full-operational Collaborative Decision Making (CDM) airport (Schiphol, 2019b). Throughout Europe, scarce time slots at airports got lost due to missing and incorrect flight information. Therefore, Airport Collaborative Decision Making (A-CDM) was initiated by Eurocontrol in order to handle air traffic in a efficient way (Schiphol, 2019e). At AAS, the introduction and development of CDM was a joint initiative of the airlines, ground handlers, LVNL and AAS (Schiphol, 2019g). The main purpose of CDM is enabling all operational partners at airports to share relevant (flight)information and data in order to optimize the turnaround process and coordination of resources. By sharing information for flights during the inbound, turnaround and outbound flight phase, the predictability of flights increases. For the turnaround process, the by Eurocontrol defined Milestone Approach is used:

"The Milestone Approach element describes the progress of a flight from the initial planning to the take off by defining Milestones to enable close monitoring of significant events. The aim is to achieve a common situational awareness and to predict the forthcoming events for each flight with off-blocks and take off as the most critical events." (Schiphol, 2019g)

For the taxiway system, CDM mainly effects the outbound flight phase. Flights are only allowed to request for pushback during the Target Start-up Approval Time (TSAT)-window (TSAT +/- 5 minutes). By using a TSAT, traffic flows on the ground can be managed. Figure 5.10 shows how the TSAT is determined by the Collaborative Pre-Departure Sequence Planning (CPDSP)-software based on the TOBT, EXOT, TTOT, CTOT (if applicable), used Standard Instrument Departure route (SID), Wake Turbulence Category (WTC) and runway capacity. The variables are explained in chronological order below, based on the CDM Operations Manual by Schiphol (2019g) and the interviews:

TOBT (Target Off-Block Time): This is the time that the ground handling processes are expected to be finished: all doors are closed and the boarding bridge and handling equipment is removed. At AAS for every Instrument Flight Rules (IFR) flight a Main Ground Handler Agent is appointed by the Airline Operator that is responsible for updating the Target Off-Block Time (TOBT). By accurate and reliable estimating the earliest possible off block time, operations on the ground are enhanced, since all airport partners get a clear overview of the intentions of the aircraft on the ground. Besides, it is important for the departure planning at the airport and for the Air Traffic Flow Management (ATFM) across Europe.

TSAT (Target Start-up Approval Time): Within the TSAT-window (+/- 5 minutes) the flight crew shall call 'Ready' when fully ready: all handling processes finished and fully ready for immediate pushback (if required) or taxi. Therefore, pushback management should use the TSAT in its tug assignment planning.

EXOT (Estimated Taxi-Out Time): A table for 'variable' taxi times is used at AAS, based on gate, runway and aircraft size (NaBo or WiBo). In the past, a static taxi time of 14 minutes for every flight was used.

TTOT (Target Take Off Time): The earliest TTOT (TTOT') is calculated for each flight by summing the TOBT and EXOT. This TTOT' is used as a starting point for the algorithm to optimize the takeoff sequence. The optimized takeoff sequence leads to an optimized start-up sequence by subtracting the Estimated Taxi-Out Time (EXOT) for each flight.

CTOT (Calculated Take Off Time): When traffic demand is expected to exceed the available capacity (either en route or at airports), the Central Flow Management Unit (CFMU) of Eurocontrol can call for "ATFM Regulations" and allocate "ATFM slots" (Calculated Take Off Time (CTOT)) to flights to regulate the flow.

According to Operations representative 1 the change of one flight's TOBT at AAS currently impacts the TSAT of nine other flights. This shows the dependency of flights to each other and underpins the importance of accurate estimations of the TOBT.

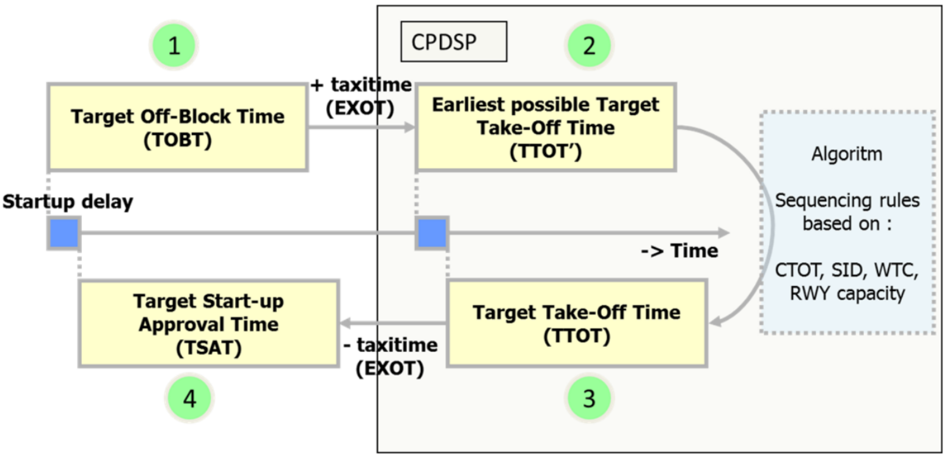


Figure 5.10: Determination of TSAT (Schiphol, 2019g)

5.3.5 Winter operations

As mentioned in Section 3.6.2, the two main procedures within the winter operation process are de-icing of aircraft and cleaning the operational surfaces of the airport. Both are elaborated for AAS below.

De-icing

As mentioned in Section 3.6.2, de-icing has to be done on locations on the airport were the de-icing fluid can be collected separately for recycling, since most of the fluids contain toxic elements. Also at AAS, de-icing is only allowed on locations where infrastructure to collect glycol is present (Prent, 2019). All aircraft stand types expect type F are equipped with glycol-collecting infrastructure. Hence, most of the aircraft at AAS are de-iced at the stand on which the flight is handled. Yet, KLM offers de-icing at a central location: stands P10-P16. All KLM flights are de-iced there, as well as SkyTeam partners and other partners (e.g. Emirates) that have contracts with KLM for de-icing (Prent, 2019).

In the interviews, Asset Manager 3 stated that the airport currently is setting up a project for more central de-icing locations in order to reduce the aircraft stand occupancy time and thus increase the gate capacity. Several interviewees mention the influence of central de-icing on the taxiway system, since the number of movements increase and detours via the de-icing facility may be required.

De-icing operations also have impact on A-CDM. The de-icing companies are required to provide and update the CDM de-icing parameters (Schiphol, 2019g). The de-icing parameters indicate:

- Where de-icing will take place;
- How long the de-icing process wil take;
- If there is a delay because of insufficient de-icing capacity;
- If a de-icing request is cancelled.

As mentioned before, two types of de-icing locations are possible at AAS: at the gate or remote. This influences the implementation of de-icing in CDM:

For gate de-icing the TOBT is used as a basis for the de-icing planning. If there is limited de-icing capacity, a De-Icing Waiting Time (DIWT) is added. Based on the TOBT, DIWT and Estimated De-Icing Time (EDIT), CPDSP will recalculate the TSAT and Target Take Off Time (TTOT) for each flight (see Figure 5.11).

Figure 5.11: Milestones of A-CDM with gate de-icing (Schiphol, 2019g)

For remote de-icing, the TSAT is used as a basis for the de-icing planning. If there is limited de-icing capacity, a DIWT is added. In this case, CPDSP will recalculate the TSAT and TTOT based on: (1) TOBT + DIWT as a new target off block time and (2) a new taxi-out time which is based on EDIT and the time to taxi from the relevant gate via the remote de-icing apron (J-apron) to the assigned runway (see Figure 5.12).

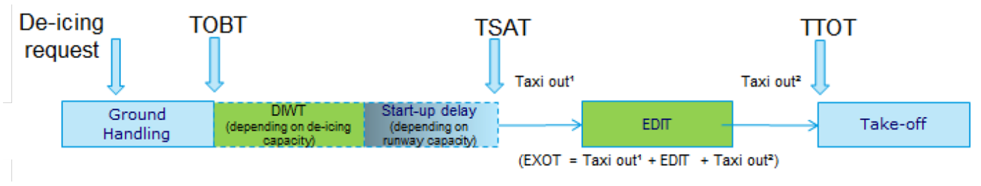


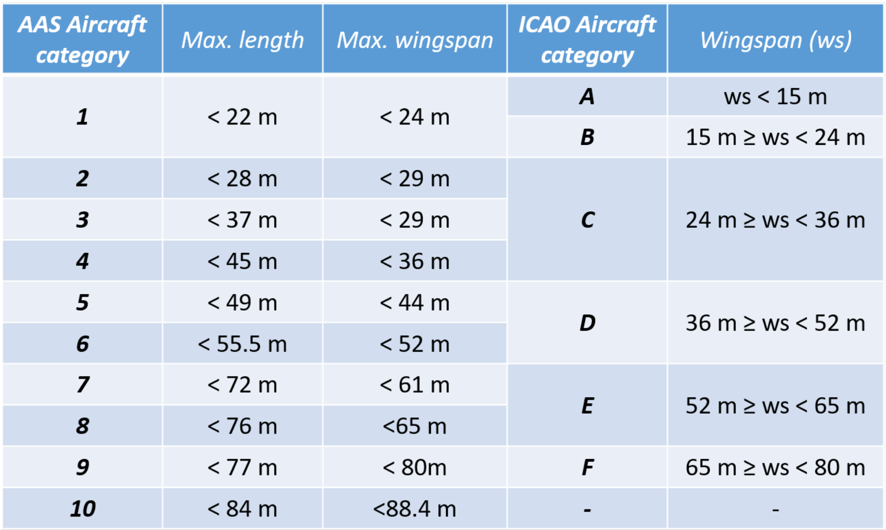
Figure 5.12: Milestones of A-CDM with remote de-icing (Schiphol, 2019g)

Cleaning of operational surfaces

The airport takes care of the mechanical clearing of the snow with ploughs and cutter blowers and also the chemical de-icing of operational surfaces (Schmitt and Gollnick, 2016). At AAS the policy for snow fighting and slippage-preventing is aimed at on-time availability of team of personnel and equipment to guarantee safety for passengers, personnel, freight and aircraft at the airport (Schiphol, 2018a). The goal of AAS is to remain open as long as possible (with safe conditions) during winter circumstances with as least as possible disruptions in the airport process.

5.4 THE TAXIWAY SYSTEM

Now the use of the airport is known, this section discusses the taxiway system at AAS. As mentioned in Section 3.5, ICAO (2018a) defined aircraft code letters corresponding to the aircraft's wingspan to enable efficient design: airport infrastructure is designed based on the critical aircraft code which the airport wants to facilitate. Yet, AAS defined its own categorization for aircraft. Instead of code letters A-F, AAS uses code numbers 1-10 (see Table 5.6). Hence, the total number of aircraft categories for AAS is four more than the standard ICAO categorization. The additional number of categories enables the airport to optimize the usage of spare space. Besides, the aircraft categories of AAS are not only based on wingspan, but also on aircraft length.



AAS Aircraft category	*Max. length*	*Max. wingspan*	***ICAO Aircraft category***	*Wingspan (ws)*
1	< 22 m	< 24 m	***A***	ws < 15 m
			B	15 m ≥ ws < 24 m
2	< 28 m	< 29 m	***C***	24 m ≥ ws < 36 m
3	< 37 m	< 29 m		
4	< 45 m	< 36 m		
5	< 49 m	< 44 m	***D***	36 m ≥ ws < 52 m
6	< 55.5 m	< 52 m		
7	< 72 m	< 61 m	***E***	52 m ≥ ws < 65 m
8	< 76 m	<65 m		
9	< 77 m	< 80m	***F***	65 m ≥ ws < 80 m
10	< 84 m	<88.4 m	**-**	-

Table 5.6: Aircraft categories AAS compared to ICAO aircraft categories (Schiphol, 2019d; ICAO, 2018a)

In taxiway design for AAS, the taxiway clearances and taxilane clearances as defined by EASA (2017) are used based on the aircraft code letter corresponding with AAS's aircraft code number. It should be noted that the design criteria of EASA (2017) are in accordance with design criteria of ICAO (2018a).

5.4.1 Characteristics

The taxiway system at AAS possesses some important characteristics. First of all, as mentioned in Section 5.3.3, AAS is primarily build up of piers. This causes blind alleys around the gates. The taxilanes between two piers are often referred to as 'bays'. For example, the area between the F-pier and G-pier (see Figure 5.9) is called the F/G-bay. At AAS, two (double) taxilanes are present between the B- and C-pier, between the C- and D-pier, and partly between the D- and E-pier. Along the G-pier, three taxilanes are available: either the two outer can be used by two NaBo (wingspan $\leq$36m, single-aisle) simultaneously, or the middle taxilane can be used by WiBo (wingspan $>$ 36m, twin-aisle).

Secondly, around the terminals and piers there is a set of main taxiways: Alpha (A) and Bravo (B). Alpha and Bravo are parallel taxiways, enabling two way traffic around the terminals and piers. In the procedures, taxiways Alpha and Bravo have standard taxi routings (directions): counter clockwise (Alpha) and clockwise (Bravo). These directions should be used, unless otherwise instructed by the ATCO. Together with taxiway Quebec (Q), taxiways Alpha and Bravo form the 'ring road' of AAS (see Figure 5.13). Currently, taxiway Quebec has no parallel taxiway, meaning that the 'ring road' of AAS is not fully build up of parallel taxiways. However, the airport initiated a project to build a parallel taxiway south to the existing taxiway Quebec (Royal Schiphol Group, 2019a).

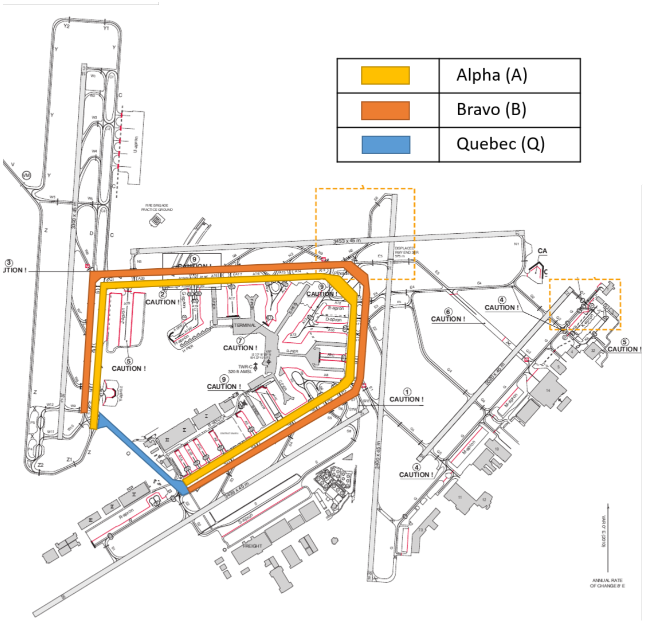


Figure 5.13: Primary taxiways at AAS

5.4.2 Procedures

As mentioned in Section 3.6, ICAO states basic rules and procedures for the aviation industry. However, airports define additional rules and procedures for their own aerodrome. The below mentioned rules and procedures for AAS are primarily based on the interviews with pilots and the ATCOs.

Taxi speed

Airports generally do not define maximum taxi speeds. The maximum allowed speed for taxiing is mainly defined by aircraft manufacturers. They determine the maximum speed for which an aircraft can taxi safely. A distinction is made between straight taxiing and taxiing in a curve (where the force on the nose-wheel is limiting). Next to the manufacturer limitations, airlines define maximum taxiing speeds for their crews. From the interviews it turned out that all four represented airlines use the following maximum speeds:

$$\begin{aligned} v_{max,straight} &= 30kts \\ v_{max,curve} &= 10kts \end{aligned}$$

Separation

Separation on the ground is partly provided by the ATCO and partly by the flight crew. The flight crew is responsible for longitudinal separation. During the interviews, pilots stated that they keep their distance naturally, like in cars. Yet, the distance they keep depends on speed and sight. Under Low Visibility Procedures (LVP) the ATCO might play a role in longitudinal separation too.

In general, the ATCO ensures safe movement over the aerodrome surface by lateral separation. However, some general rules and procedures apply. Next to the by International Civil Aviation Organization (ICAO) stated rules, pilots mentioned the following rules for AAS:

- Traffic vacating the runway has priority[2];
- At most airports, traffic coming from taxilanes (bays) have to stop (regardless of coming from the right), but at AAS traffic from the right (taxiway or taxilane) has priority if it comes from the right hand side;
- Taxiing aircraft have priority over towing movements;
- Taxiing aircraft have priority over vehicles.

Other typical AAS procedures

From the interviews, it came forward that there are some procedures that are very typical for Schiphol:

- At AAS 'Ground'-control uses four different frequencies, since on peak moments four ATCOs can be active. Hence, during taxiing possibly the flight crew has to change the frequency up to three times.
- After landing, there is an 'automatic' frequency change from the applicable 'Tower'- to the applicable 'Ground'-frequency at AAS, meaning that the flight crew has to change frequency without an instruction of an ATCO.
- 'Ground'-controllers at AAS ruse relatively short taxi instructions. Rather than mentioning all the taxiways on the route, they mention some intersections (nodes) and most important taxiways.

5.5 TAXIWAY SYSTEM PROCESSES

Wasson (2015) states that the first step in Systems Engineering (SE) is getting insights on (1) *who* a system's stakeholders are, (2) *what* they expect the system to accomplish, and (3) *how well* the outcome is to be achieved in terms of performance. This is a critical step and it forms the basis for deriving a system from which specification requirements can be derived. Therefore, first a use case diagram is developed for the taxiway system at AAS. Next, the identified use cases are described. For the main use cases, activity diagrams are developed to elaborate in more detail on the interactions between actors.

5.5.1 Use case diagram

A use case diagram captures a system's functionality as seen by its users (Ahmad and Saxena, 2008) and gain insights in the system's functional requirements (Fowler, 2003). Through an outside-in view, it shows the possible procedures in the use of

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[2] Due to the orientation of runways and the defined directions on taxiway Bravo, traffic vacating the runway has priority also follows from traffic from the right has priority at the runways at AAS.

the system. A use case describes a set of sequences of actions, including variants (Booch et al., 1999).

The developed use case diagram for the Taxiway System at AAS is shown in Figure 5.14. As can be seen, two primary and five secondary actors (generalized to two) can be identified: the Flight Crew (pilot) and Aircraft are primary actors. The Flight Crew is part of the Aircraft (generalization). The secondary actors are 'Tower'-control and 'Ground'-control, both part of LVNL (ATC). For the towing of aircraft, the Ground Handler plays a role. Besides, AAS' Operations and Asset Management departments are secondary actors. Section 5.6 further elaborates on these stakeholders' objectives and introduces other (indirect) stakeholders.

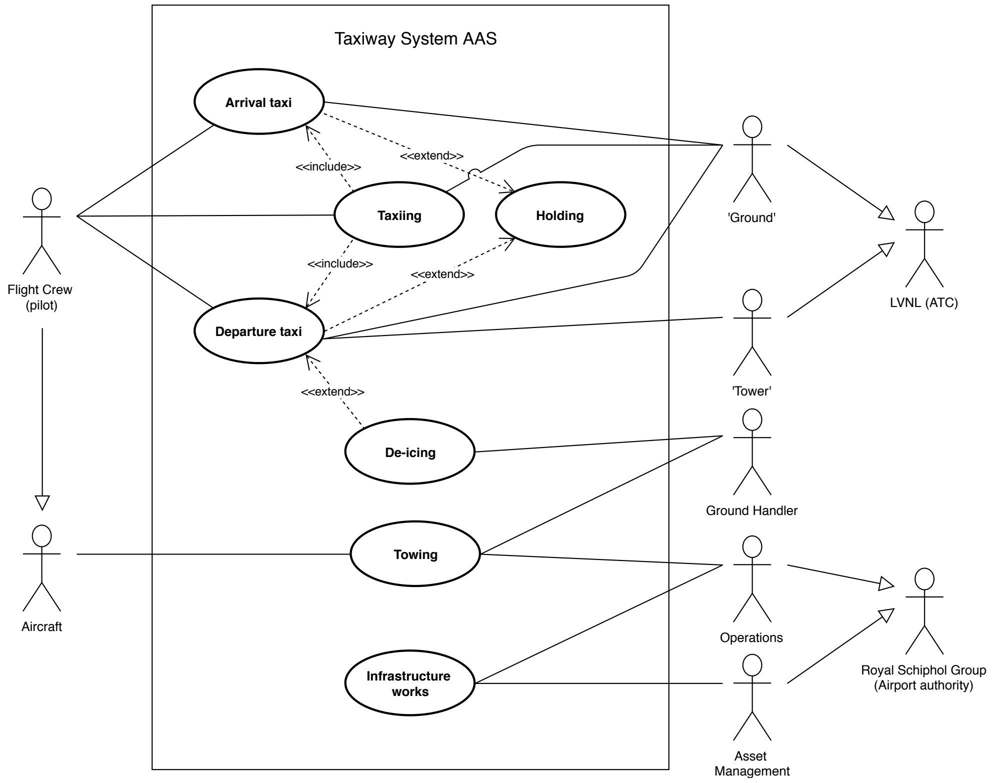

Figure 5.14: Use case diagram of the Taxiway System at AAS

The developed use case diagram shows four core use cases: Taxi In, Taxi Out, Towing and Infrastructure works. Within the *Arrival taxi* and *Departure taxi* use cases, *taxiing* is an included use case. Besides, *holding* is an excluded use case to the taxi in and taxi out use cases. Moreover, within the Departure taxi, *De-icing* is an excluded use case. As mentioned before, de-icing itself does not necessarily take place within the taxiway system, but it might require additional movements within the taxiway system and is therefore considered in the use case diagram. *Towing* is used for relocating aircraft at the airport. Besides, *Infrastructure works* (e.g. maintenance) can be performed within the taxiway system. The identified use cases are elaborated in the following sections. Activity diagrams for *Arrival taxi*, *Departure taxi* and *taxiing* are provided at the end of this section on pages 77 - 79.

5.5.2 Arrival taxi process

The Arrival taxi process (see Figure 5.17) starts right after touch down of the aircraft when the cockpit intercepts the taxiway center line, as defined in Section 3.8 . Once the flight crew decelerated the aircraft to taxi speed, completed the after landing checklist and contacted the right 'Ground'-controller, the 'Ground'-controller will either instruct the aircraft to taxi to the assigned stand or, when for example the stand is not yet available, to a holding location first. Part of the taxi in process is the taxiing, which thus is an included use case. Therefore, this process is elaborated into more detail in Section 5.5.4. Before entering the stand, the flight crew has to verify the availability of the VDGS or the presence of a marshaller at the stand. They are not allowed to enter the stand without one of these. The taxi in process ends when the aircraft enters the stand.

5.5.3 Departure taxi process

The Departure taxi process is shown in Figure 5.18. The Departure taxi process can only start within the TSAT-window (+/- 5 minutes) and when en-route clearance is received and the aircraft is fully ready for pushback (including eventual gate de-icing). Once the 'Ground'-controller has issued start-up and pushback clearance and the aircraft is ready to taxi, the 'Ground'-controller will either instruct the aircraft to taxi to the assigned runway or, when for example the TTOT can not be met, to a holding location first. Part of the departure taxi process is the taxiing, which thus is an included use case (see Section 5.5.4). Once the aircraft reaches the runway, it contacts 'Tower'. The 'Tower'-controller either decides to let the aircraft hold short (say nothing), immediately provides takeoff clearance, or first instructs the aircraft to line up and wait. The taxi out process ends when the the flight crew confirms the takeoff clearance and applies takeoff power.

5.5.4 Included and extended use cases

Included: taxiing

As mentioned before, the taxiing process is an included use case for the taxi in and taxi out use cases. After the 'Ground'-controller issues the taxi instruction, the taxiing process starts (see Figure 5.19).

As long as the instructed destination is not reached and as long as no intermediate holding position is reached, a continuous loop starts. At all times, the flight crew should follow the applicable procedures, as mentioned in Section 5.4.2. Besides, while taxiing, the aircraft is guided by the 'Ground'-controller. Hence, the 'Ground'-controller follows the aircraft's position on the airport and its relative position to other aircraft and detects potential conflicts. In case of a potential conflict, the ATCO will instruct (one of) the aircraft to perform a preventive action (e.g. giving way to another aircraft). If the aircraft is about to enter another 'Ground'-control area, the 'Ground'-controller will instruct the flight crew to change frequency to the other 'Ground'-frequency. When the aircraft was instructed to taxi to a hold short location and this location is reached, the flight crew will request clearance to continue taxiing. Once the final destination of the taxi route is reached (either a stand, a holding bay or a runway entry), the taxiing process ends.

Extended: holding

Depending on the expected holding time, the 'Ground'-controller will instruct the flight crew to taxi to either a holding bay, or wait at a taxiway. During holding the engines are not switched of to ensure the possibility to continue taxiing as soon as possible.

Extended: de-icing

In case the aircraft shall be de-iced through remote de-icing (see Section 5.3.5) during the departure taxi process, the 'Ground'-controller will instruct the aircraft to the de-icing location before verifying if the TTOT can be met and instructing the aircraft to taxi towards the runway (or to a holding location first after de-icing). The de-icing itself at AAS does not take place within the taxiway system, but remote de-icing requires additional taxi movements of aircraft.

5.5.5 Towing

When an aircraft has to be relocated at the airport, it is towed by a towing truck. In other words, each aircraft movement not being an arriving or departing flight, is a towed movement. Tow movements are executed by ground handlers with towing trucks. Most of these movements are from gates to parking positions for intermediate parking and back (see Section 5.3.3), or from gates to hangars for maintenance and vice versa. At AAS towing is performed under guidance of Apron Control, which is *not* part of ATC, but part of the airport's Operations department. This Apron Controller, however, coordinates towing movements with the 'Ground'-ATCOs, since both controllers are active in the same movement area. The Apron Control guidance at AAS is split up in two areas: North and South. Hence, two Apron Controllers can be active simultaneously. The interviewed Apron Controller mentioned that as long as ATC uses two 'ground'-controllers in the central area of AAS, Apron Control operates with two controllers as well. Accordingly, generally during day time two Apron Controllers are active, where only one Apron Controller is active during night time.

In 'part 1.2.4 Executing Towing Movements' of the 'Business Area Aviation Manual' of AAS (Schiphol, 2018c), rules for towing movements are listed. Below, five important rules for executing towing movements are provided:

- Before starting the towing movement, all doors and shutters of the aircraft have to be closed;
- The towing truck driver requests clearance from the Apron Controller for executing the towing procedure;
- The towing truck driver uses standard towing routes, unless otherwise instructed by the Apron Controller (see Appendix E;
- At specified locations, the towing truck driver should receive clearance from the Apron Controller before crossing the location (e.g. runways);
- During towing, a certified person is in the towed aircraft's cockpit to control the brakes (often a certified ground handler representative).

As can be seen in Appendix E, West of Runway 18C / 36C, no tow routes are available. In the area West of this runway, no 'normal' tow movements are allowed. In case an aircraft has to be towed to/from this area, the movement takes place under guidance of a marshaller-vehicle, which will be in contact with the 'Ground'-controller, not the Apron Controller.

The interviewed Apron Controller mentioned that peaks in tow movements can be found during the morning and in the night. In the morning, after the first intercontinental inbound peak, many WiBo are intermediate parked and thus towed from the gates to the buffers. After the second intercontinental peak (most of these aircraft are not intermediate parked), the aircraft that arrived first are towed back to the gates to prepare for their outgoing flight. In the night most of the tow movements to- and from the maintenance hangars take place. During daytime these movements are minimized, since two runways have to be crossed between the central traffic area and the maintenance area (see Figure 5.8).

5.5.6 Infrastructural works

Within the taxiway system, different types of infrastructural works can be carried out. In theory, all assets can be maintained. In practice, however, infrastructural works are challenging both in planning and execution, since the operation of an airport should be influenced as less as possible. Since AAS is open 24/7, planning infrastructural works is even a bigger challenge. Within the operations department, the sub-department Works and Asset Planning (WAP) is responsible for planning all infrastructural works at AAS. The operations department also declares periods and locations where no infrastructural works should be planned, based on the operation (e.g. if demanded capacity can not be met). For large projects, plans are often made years ahead.

Yearly, a meeting takes place with involved stakeholders (LVNL, airlines, concerned AAS departments, and the Omgevingsraad Schiphol (*Environmental Council Schiphol*) (ORS)) to discuss all scheduled work for the year ahead. Besides, the operations department remains in contact with major local stakeholders (i.e. LVNL and KLM) throughout the year to discuss all infrastructural works. The ORS is represented in the yearly meeting since runway works influence the noise disturbance for local residents since other runways might have to be used.

Below, first large projects are briefly described further, followed by the regular maintenance regime at AAS for the taxiway system. In the end, cleaning of operational surfaces during winter operations is described.

Large infrastructural projects

Larger projects regularly start with a request or a problem (see Figure 5.15). Often, these inputs originate at the operations department, where faced issues in the day-to-day operation pop up. Once the request or problem is recognized and honored, a tactical plan is defined. Next, the Asset Management department comes up with an investment proposal. This proposal is based on a study of variants, budgets, safety assessment and functional requirements. From the investment proposal, a proposed solution comes forward. Within Royal Schiphol Group, PLUS is the project organisation that executes the project. Once the project is finished, the infrastructure is handed over to the Asset Management department, which is responsible for its management and maintenance. According to the interviewed Asset Management representatives, regular larger infrastructural projects on average have a lead time of two years.

Amongst large infrastructural works are also larger maintenance works for the runways. In the last years, AAS developed a runway maintenance strategy, in which they stated how to deal with maintenance of runways. For the taxiway system, not such strategy was developed yet. However, according to Operations representative 1, the asset management department initiated working on a taxiway system maintenance strategy.

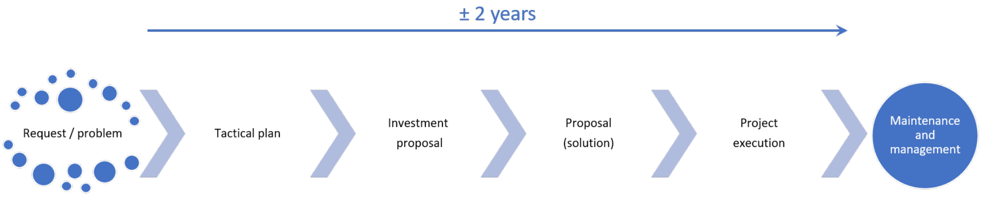

Figure 5.15: Phases for infrastructural projects at AAS (based on interview with Asset Manager 3)

Small (regular) maintenance

The Asset Management department is primarily responsible for maintenance of the taxiway system at AAS. Regular (small) maintenance is outsourced to contractors through maintenance contracts[3]. These contracts are result-based. To get to this maintenance contract, the operations and asset management departments had to harmonize: the operations department prefers the norms (e.g. level of quality, time frame for resolving malfunctions) to be high, but that would result in high costs, which the asset management department wants to keep low. Hence, a balance between norms and costs had to be fined. The contractor defines a maintenance plan, based on the state of the infrastructure. Annually, an infrared scan is made of the taxiways' surfaces to check the quality of the infrastructure. If certain spots require maintenance relatively often, monitoring projects are initiated for these locations in order to ensure constant high quality of all infrastructure.

Cleaning of operational surfaces

At AAS the policy for snow fighting and slippage-preventing is aimed at on-time availability of team of personnel and equipment to guarantee safety for passengers, personnel, freight and aircraft at the airport (Schiphol, 2019g). The goal of AAS is to remain open as long as possible (with safe conditions) during winter circumstances with as least as possible disruptions in the airport process. Figure 5.16 shows the snow fighting team at AAS in action.

Figure 5.16: Snow fighting at AAS (Schiphol, 2019i)

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[3] Since 1 April 2019 Heijmans is the responsible contractor for maintenance of parcel 1 (Runways and Taxiways) at AAS.

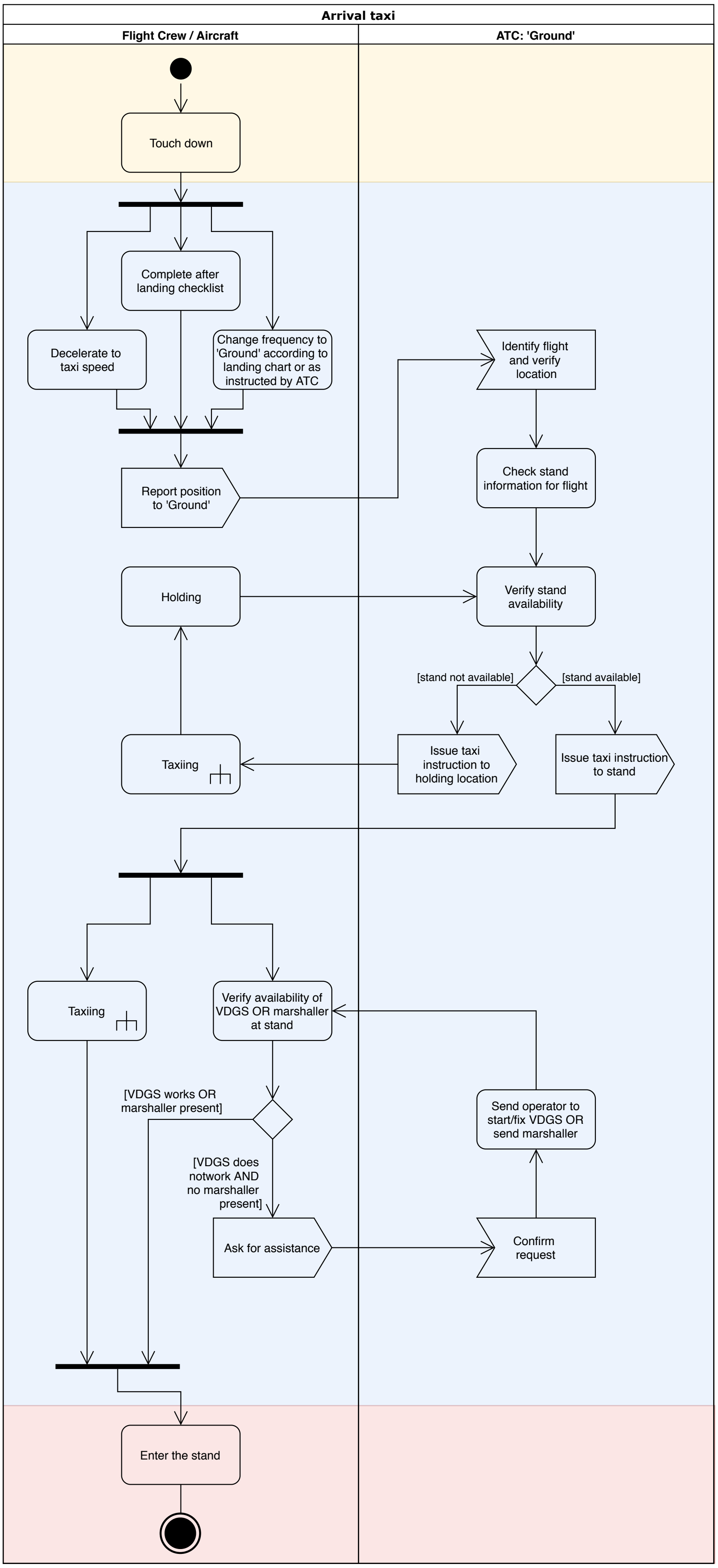

Figure 5.17: Activity diagram of the Taxi-In process AAS. Blue shows the boundary of the taxiway system as defined in Section 3.8. Besides, yellow shows the runway area and red shows the area outside the ATC boundary line (aircraft stand).

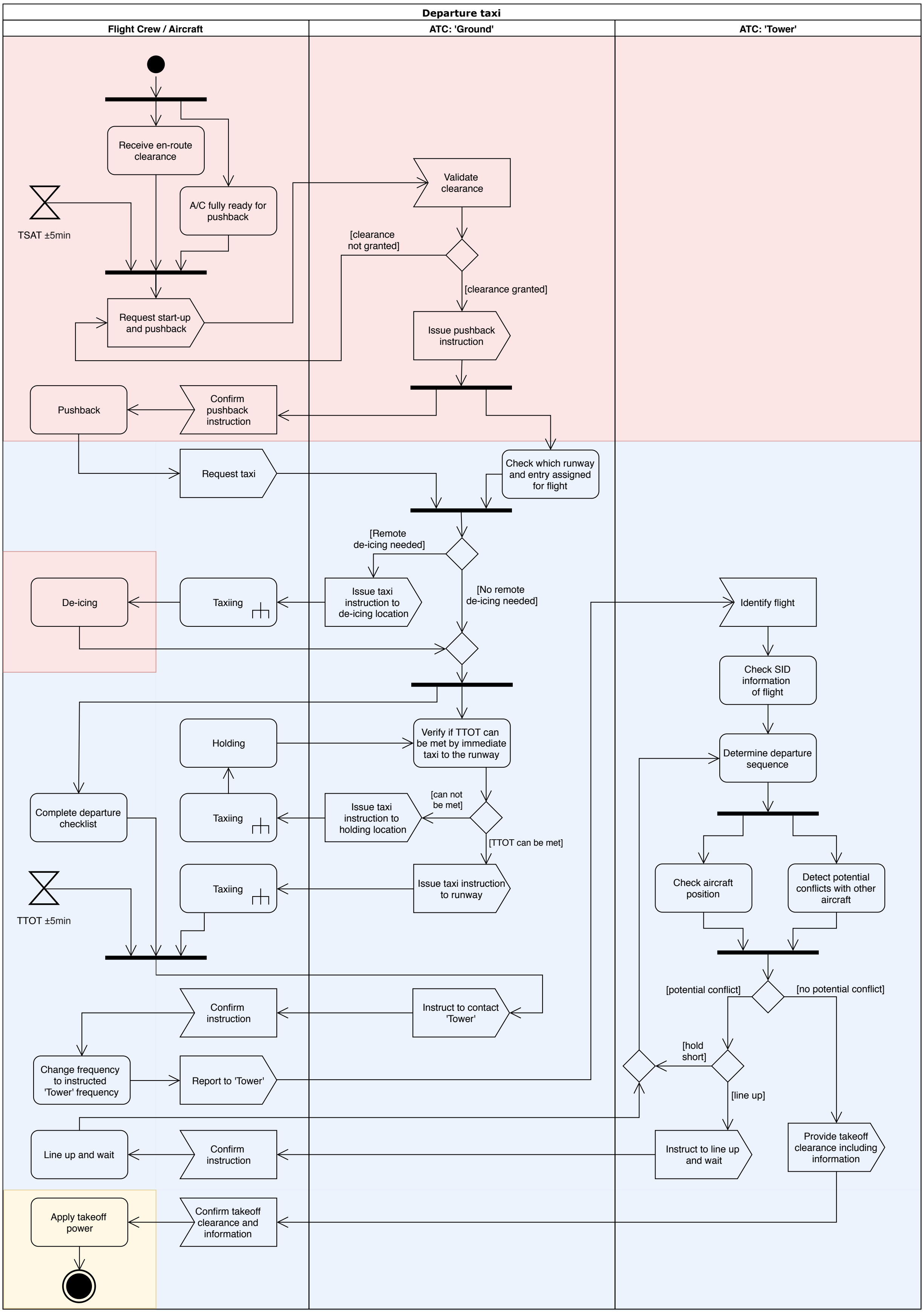

Figure 5.18: Activity diagram of the Taxi-Out process AAS. Blue shows the boundary of the taxiway system as defined in Section 3.8. Besides, red shows the area outside the ATC boundary line (aircraft stand) and yellow shows the runway area.

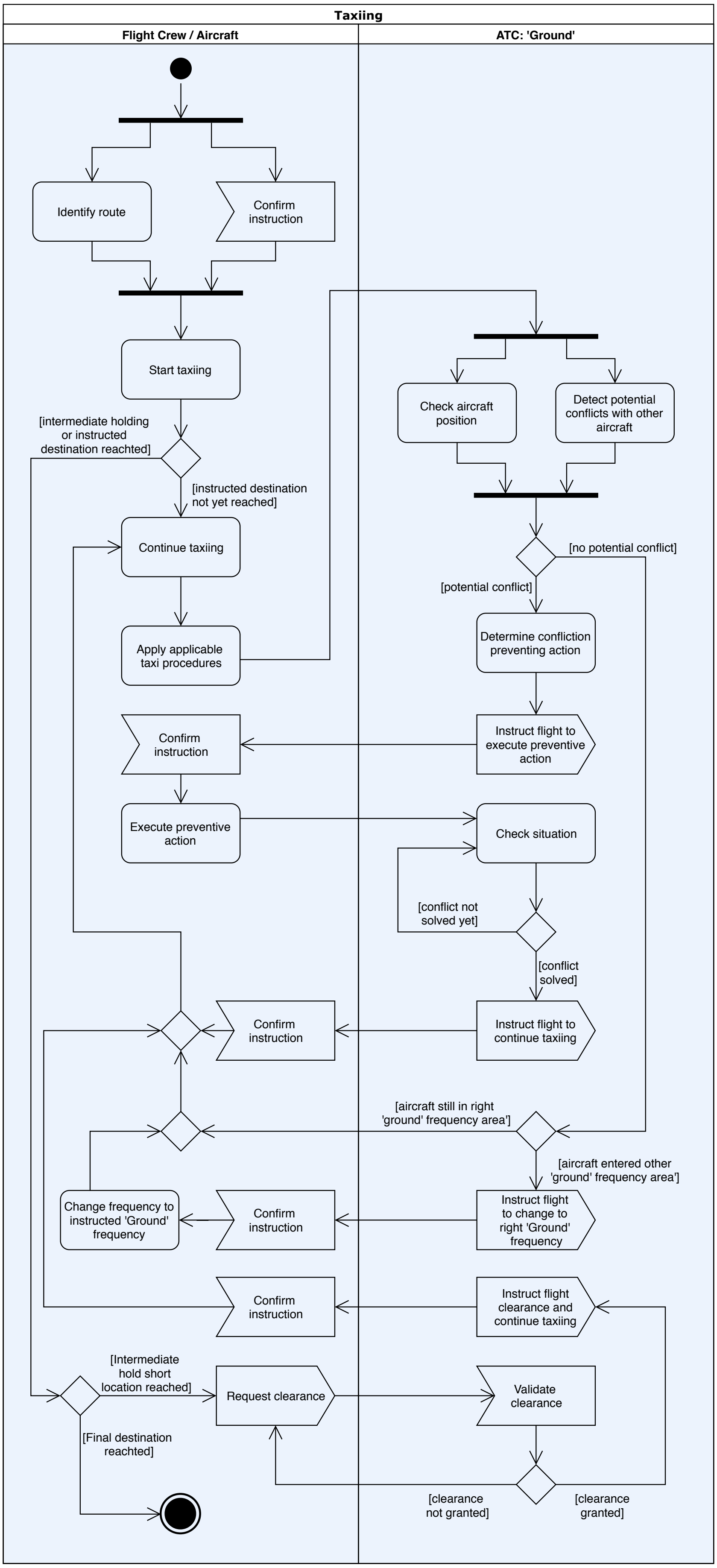

Figure 5.19: Activity diagram of the Taxiing process within the taxiway system at AAS.

5.6 STAKEHOLDER ANALYSIS

As mentioned in Section 2.5, considering and understanding the involved stakeholders is critical in a managed system, since it gives insights in the relevance of stakeholders to the system (Brugha and Varvasovszky, 2000; Murray- Webster and Simon, 2006). In this thesis, a stakeholder analysis is used to provide insights on involved stakeholders to taxiway systems, and their objectives and preferences related to taxiway systems. The methodology as described in Section 2.5 will be used. Hence, in Section 5.6.1 the involved parties are described, based on the in Section 3.7 identified actors. Next, in Section 5.6.2 the levels of power and interest of all involved stakeholders are discussed and graphically shown.

Information in this section is primarily based on literature by Idris et al. (1998), Lee and Balakrishnan (2010), Potts et al. (2009), Schmitt and Gollnick (2016) and the performed interviews.

5.6.1 Involved parties

Figure 5.20 provides an overview of the stakeholders involved in the taxiway system at AAS. Afterwards, the stakeholders are described and their objectives provided. The stakeholders are categorized per actor as identified in Section 3.7.

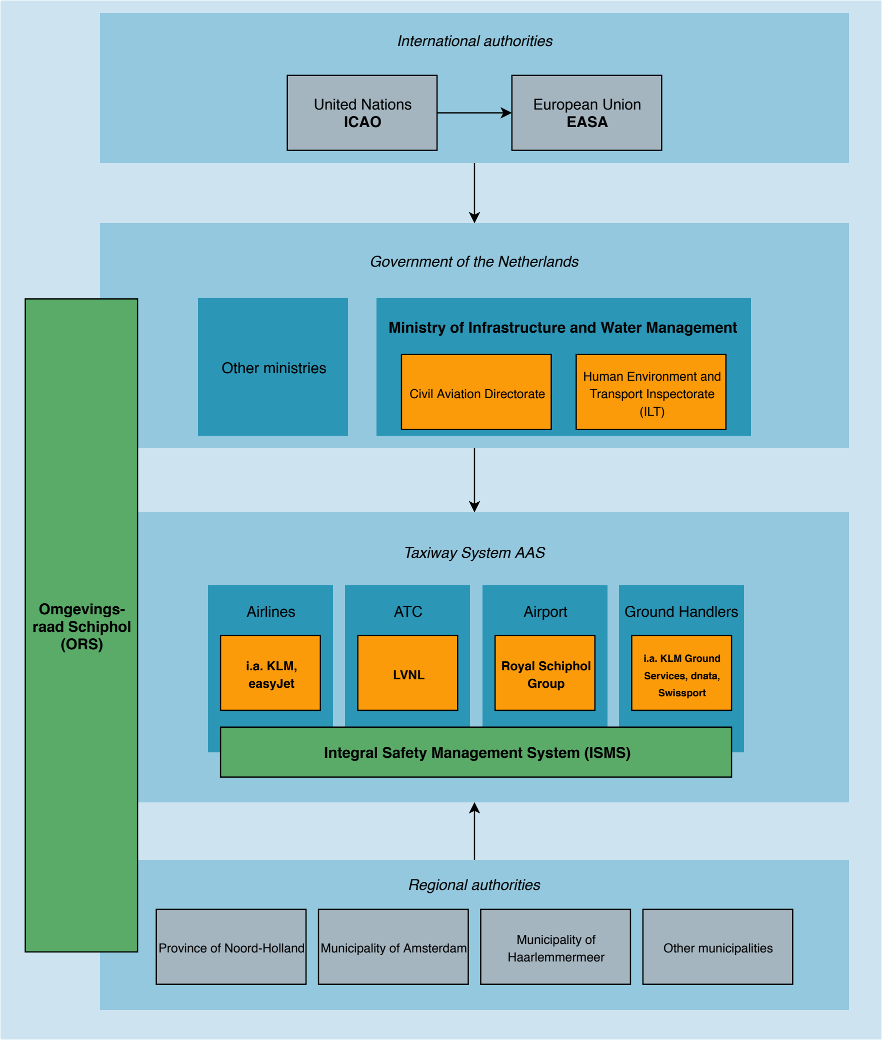

Figure 5.20: Overview of stakeholders related to the taxiway system at AAS. Stakeholders in bold are directly related to the taxiway system. Adapted from Dutch Safety Board (2017)

Aircraft and Flight Crew

As mentioned in Section 3.7, the aircraft is the end user of taxiway systems. However, the airline operating the aircraft sets the objectives for usage of the taxiway system by the aircraft. Therefore, airlines are considered as stakeholders representing the actor *aircraft*. At AAS, as mentioned in Section 5.3, **Royal Dutch Airlines (KLM)** is the major airline (together with its SkyTeam partners, i.a. KLM Cityhopper, Transavia, Delta Airlines), followed by **easyJet** (Royal Schiphol Group, 2019a). Both interviewed pilots as well as AAS-representatives mentioned that representatives of these airlines are involved in meetings on for example planning of infrastructural works. Besides, airlines are represented by the **Board of Airlines Representatives In the Netherlands (BARIN)**, which is the industry association for airlines undertaking business in The Netherlands.

The objectives of airlines in the taxiway system are:

- Maximize the safety of operations;
- Minimizing the operating costs (especially fuel costs);
- Minimizing the engine run times before takeoff;
- Maximizing the punctuality regarding the landing/takeoff; time in published timetables.

As major operator of aircraft, flight crews also are important stakeholders. During taxiing, flight crews operate the aircraft. They are represented by their airlines, but also through the **Vereniging Nederlandse Verkeersvliegers (*Dutch Airline Pilots Association*) (VNV)**). During the interviews, the following objectives for the taxiway system were mentioned by pilots:

- Maximize the taxiway system clearness and logic to prevent mistakes ("self-explaining" system);
- Maximize uniformity over the airport for all components;
- Especially at busier airports, ATC should be as clear as possible;
- Visual aids should be applied and in good condition to increase situational awareness.

Air Traffic Control

As mentioned in Section 3.7, Air Traffic Control (ATC) can be seen as both a user and enabler in the taxiway system: ATCOs use the airport's infrastructure and by guiding aircraft they enable them to manoeuvre on the airport's surface. At AAS, ATC on the ground is split up in 'Ground'- and 'Tower'-control, both with multiple frequencies. Both ATC functions are at AAS executed by **Air Traffic Control the Netherlands (LVNL)**.

LVNL's core activity is providing Air Traffic Services within the Amsterdam Flight Information Region. Besides, LVNL is amongst others responsible for maintaining the required technical systems, providing aeronautical information and aeronautical maps and publications - including procedures (LVNL, 2019b). Hence, LVNL is responsible for defining procedures within the taxiway system. Yet, as mentioned in Section 2.2, unfortunately no interviews were held with representatives of LVNL. Consequently, identified objectives are based on statements by other interviewees.

'Tower'-control is responsible for all traffic within the runway strip (on the runway side of runway holding positions): landings and takeoff clearances, as well as runway crossing clearances. At AAS, depending on the traffic demand, up to four 'Tower'-frequencies can be used simultaneously. Hence, at peak moments, up to four 'Tower'-controllers can be active simultaneously. The following objectives are identified for 'Tower'-controllers:

- Minimizing the arrival/departure delay
- Maximizing the runway throughput

'Ground'-control is responsible for all aircraft manoeuvring on the airport's surface on their own power (taxiing), not being within the runway strip. At AAS, depending on the traffic demand, up to four 'Ground'-frequencies can be used simultaneously. Hence, at peak moments, up to four 'Ground'-controllers can be active simultaneously. The 'Ground'-controller is in direct contact with the flight crew and provides taxi instructions. During taxiing, the controller monitors all aircraft movements in his/her area of responsibility and when needed instructs flight crews to make preventive actions (e.g. giving way to another aircraft, hold short). The following objectives are identified for 'Ground'-controllers:

- Enable safe movement of aircraft
- Enable smooth movement of aircraft
- Simplify taxi instructions
- Minimize preventive actions
- Minimize conflicting flows
- Ensure interpretability in only one way
- Minimize runway/taxiway intersections
- Maximize independency within the taxiway system

In order to reach the ATCOs objectives, they prefer the taxiway system to offer as much flexibility as possible. In other words, ATCOs prefer many links, since it enables them to route aircraft via many different routings. Besides, they prefer flexibility in the procedures for usage of the system.

It should be noted that towed traffic is not guided by 'Ground'-control but by 'Apron'-control, which is not part of LVNL, but of Royal Schiphol Group - which will be discussed later. However, the 'Ground'-controller is in contact with the airport's Apron Controller to coordinate tow movements where needed.

Airport

The airport authority of AAS is **Royal Schiphol Group**. With AAS as major operating airport, the group is also the airport authority of Rotterdam The Hague Airport, Lelystad Airport and has a majority interest in Eindhoven Airport. Moreover, Royal Schiphol Group has interests in international airports world wide. With 69.77% of the shares, the Dutch Government is the major shareholder of the Royal Schiphol Group, followed by the municipality of Amsterdam (20.03%) (Schiphol, 2019h).

For AAS, Royal Schiphol Group is divided in four business areas, of which the business area 'Aviation' is responsible for the key activities: servicing passengers, airlines, ground handlers and logistics service providers. Through this business area, the group facilitates aircraft (and ATC) to use the taxiway system by providing needed infrastructure and ensuring reliable, safe and efficient operations.

Within the 'Aviation' business area, multiple departments with different responsibilities are active. The **Airport operations** department facilitates and directs all processes that are needed for passengers and airlines. Hence, they are responsible for facilitating aircraft to move on the airport's surfaces, as well as snow- and ice-defence. From the interviews with airport operators, the following objectives for the taxiway system are identified:

- Maximize safety of operations;
- Maximizing the punctuality relative to the operating schedule;
- Minimizing delays on the taxiway system to minimize the need for gate changes due to delays.

Within the operations department of Royal Schiphol Group, also **Apron Controllers** are active. They control and guide all towing traffic on the airport's surface, in coordination with the active 'Ground'-controller. The interviewed Apron Controller stated that the situation at AAS is unique, since different controllers are operating in the same are. However, since taxiing traffic has privilege over towing traffic, Apron Controllers listen to the 'Ground'-frequency to adjust their actions to the activities of the taxiing traffic as instructed by the 'Ground'-controller. According to the interviewed Apron Controller, they prefer the taxiway system to be spacious. This enables them to execute towing movements as much as possible without interfering with taxiing traffic. Hence, they prefer independency of other traffic.

Another concerned department within the 'Aviation' business area of Royal Schiphol Group is **Asset Management**. This department is responsible for maintenance and management of the infrastructure and related systems, as well as developing new assets. From the interviewed Asset Managers, the following objectives for the taxiway system are identified:

- Minimize maintenance costs
- Maximize standards compliance to ensure safety

In order to minimize the maintenance costs, different measures can be used. Asset Manager 3 mentions that more infrastructure always leads to higher maintenance costs. Off course, the quantity of pavement plays an important role. However, also the lighting plays an important role: the more links with center lighting, the more lights that have to be maintained, Asset Manager 3 mentions.

In the end, Operations representative 1 and Asset Manager 3 underpinned that Royal Schiphol Group only *facilitates* and not *operates* (which do the airlines and LVNL). Consequently, AAS is not fully responsible for how assets are used. Hence, to achieve safe operations, other stakeholders should cooperate with Royal Schiphol Group. Also various investigations of accidents and serious incidents show that the risks at the interfaces between organizations are an important factor in the further improvement of safety (Daams, 2019). Therefore, at AAS, the airport airlines, ATC, ground handlers and refueling services joined forces in the **Integral Safety Management System (ISMS)** to manage safety risks together. In this way they followed up on recommendations of the Dutch Safety Board to strengthen the industry-broad co-operation on safety (Dutch Safety Board, 2017). The ISMS takes an integral approach to the management of safety interfaces at AAS with a structure that mimics the best practices for safety management systems as described by ICAO (Daams, 2019). The following organizations are involved in ISMS (Daams, 2019):

- airport: Royal Schiphol Group (AAS)
- ATC: LVNL
- airlines: KLM and easyJet
- Ground handlers: KLM and Swissport
- Gezamenlijke Tankdiensten Schiphol (*Joined Fueling Services Schiphol*) (GTS)

EasyJet, Swissport and GTS have a representative role: easyJet represents all AAS-based airlines (except KLM), Swissport represents all ground handlers (except KLM), and GTS represents the refueling services.

Ground Handlers

Besides executing the ground arrival and departure process at the apron (e.g. (un-)loading of baggage), the ground handlers also execute the eventual towing movements within the taxiway system at AAS.

At AAS, the following ground handling companies are active:

- KLM Ground Services
- Swissport
- Aviapartner
- dnata
- Menzies

Airlines have contracts with ground handlers for executing specific activities at AAS. Not necessarily all activities are executed by the same handler. For example, Emirates' ground processes are executed by dnata, where the de-icing is performed by KLM Ground Services.

The ground handlers as users of the taxiway system for tow movements are assumed to have similar objectives as flight crews, since both operate comparably within the taxiway system.

Authorities

As can be seen in Figure 5.20, three levels of authorities are involved: international authorities, the Government of the Netherlands and regional authorities.

On the highest international level, the United Nations' **International Civil Aviation Organization (ICAO)** is a specialized agency, which was established in 1944 to manage the governance and administration of the Convention on International Civil Aviation (Chicago Convention). Together with the United Nations' member states and the aviation industry, ICAO works to reach consensus on international civil aviation Standards and Recommended Practices (SARPs). Besides, ICAO works on policies to support a safe, efficient, secure, economically sustainable and environmentally responsible ATS, including taxiway systems (ICAO, 2019).

One level lower, on European level, the **European Union Aviation Safety Agency (EASA)** is the core of the European Union's strategy for safe aviation (EASA, 2019a). Part of the agency's resources to achieve this, is developing and promoting the highest common standards. Through inspections, the agency monitors the implementation of standards in the member states. The by EASA published standards are based on the by ICAO published SARPs.

As mentioned before, the Government of the Netherlands is the largest shareholder of the Royal Schiphol Group. Hence, on the national level several Ministries[4] are involved. Within the Ministry of Infrastructure and Water Management, the Civil Aviation Directorate is responsible for aviation - and thus AAS. The Ministry sets regulations and monitors whether the airport operates within these regulations. Part of this monitoring is done by the Inspectie Leefomgeving & Transport (*Human Environment and Transport Inspectorate*) (ILT). Hence, the Ministry of Infrastructure and Water Management has the largest influence on the airport and taxiway system,

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[4] Ministry of Infrastructure and Water Management, Ministry of Finance, Ministry of Economic Affairs and Climate Policy and Ministry of the Interior and Kingdom Relations.

since they set regulations related to operations. These regulation primarily focus on safety and environmental impact.

In the end, on regional level, both the Province of Noord-Holland, as well as the municipalities of Haarlemmermeer and Amsterdam play a role. The province and the municipality of Haarlemmermeer provide parts of the needed permits, since the airport is located in this municipality and province. The municipality of Amsterdam plays as second largest shareholder an important role as well for the airport. Yet, both the province and municipalities have a limited importance for the taxiway system, since they have no direct influence on the system.

Local residents

Through the **Omgevingsraad Schiphol (*Environmental Council Schiphol*) (ORS)**, local residents of AAS are represented. According to the ORS, AAS has a relative large impact on its living environment (ORS, 2019). Finding a balance between the development of the aviation sector and AAS, increasing the quality for the living environment and possibilities of usage of the space around the airport is a process in which many parties en concerned interests are involved. Hence, within the council, issues, interests and parties related to the development of Schiphol and the surrounding area are brought together and discussed. Under charge of one chair, the ORS exists of an Advisory Board and a Region Forum with both their own tasks and programs.

The main objective of the Advisory Board is to negotiation and provide advise on the strategic frameworks for the development of AAS and its surrounding area. Within the Advisory Board, the following parties are represented:

- The Government of the Netherlands
- Schiphol Administrative Directorate[5]
- Local residents
- KLM
- LVNL
- Royal Schiphol Group
- BARIN
- VNO-NCW West (business representative)
- Environmental Federation Noord-Holland (environmental organizations representative)

For the Region Forum, the focus is on the provision of information and the broader dialogue on developments in the Schiphol area. Within the Region Forum, the following parties are represented:

- Representatives of the provinces of Noord-Holland, Zuid-Holland, Utrecht and Flevoland
- Representatives of clusters of municipalities
- Representatives of five geological clusters around the airport
- The ministry of Infrastructure and Water Management

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[5] The Schiphol Administrative Directorate (*Bestuurlijke Regie Schiphol*) exists of the provinces and municipalities located (partly or completely) within the 48Lden contour of AAS, representing 4 provinces and 56 municipalities (Provincie Noord-Holland, 2018)

- KLM
- LVNL
- Royal Schiphol Group
- BARIN
- VNO-NCW West (business representative)
- Environmental Federation Noord-Holland (environmental organizations representative)

It should be noted that represented local residents in the ORS primarily live within the arrival and departing routes to and from AAS. The hindrance caused within the taxiway system is limited to direct neighbours of the airport. Therefore, the role of the ORS in relation to the taxiway system is limited.

5.6.2 Stakeholders' power and interest

Based on the stakeholders as explored in Section 5.6.1 and the methodology as provided in Section 2.5, a Power-Interest grid has been created for the system (see Figure 5.21). The relative power and interest of each stakeholder were estimated by the author of this thesis, based on gained insights throughout the research (both literature and interviews).

Figure 5.21: Power-Interest Grid

It is argued that both Royal Schiphol Group and LVNL have high power and high interest (players) in the taxiway system at AAS. However, as owner of the assets, Royal Schiphol Group has slightly higher power, where LVNL has slightly more interest, since they not only use the taxiway system, but also set procedures. For Royal Schiphol Group, based on the insights gained through the interviews, both related departments (Operations and Asset Management) have similar levels of interest in the taxiway system.

As end users, airlines and flight crews (represented by KLM, BARIN, easyJet and VNV) have similar interests as LVNL, however with less power (subjects). The ground handlers (KLM Ground Services, Aviapartner, Swissport, Menzies and dnata) as other users of the taxiway system -for tow movements- turned out to have very limited power and have less interest (crows). This might be explained by the fact that their objectives for the taxiway system are comparable to the objectives of flight crews, or even less. Hence, as long as flight crews are represented and satisfied, ground handlers are satisfied as well.

International authorities do not play an active role in taxiway systems of particular airports (limited interest. Yet, their power is high (context setters) since they define the design criteria for taxiway systems. However ICAO defines SARPs, EASA regulations are applicable at AAS. Therefore, EASA has a slightly higher power than ICAO. As major provider of required permits and as major representative of the government, the Dutch Ministry of Infrastructure and Water Management has a slightly higher interest compared to international authorities. The regional authorities have limited power and interests (crows).

In the end, the local residents represented by the ORS have medium interest and power (crows). Especially for the taxiway system, their interest is limited, since most of the noise disturbance is caused by takeoffs and landings.

5.6.3 Conclusion

From the performed stakeholder analysis, several conclusions can be drawn. With the highest power and high interest, Royal Schiphol Group is as owner of the assets of the taxiway system the most important stakeholder (with most activity from the operations and asset management departments), followed by LVNL, which is responsible for assigning infrastructure to flights and guide them through the taxiway system. Hence, both Royal Schiphol Group and LVNL are identified in the power-interest grid as 'Players' (high power, high interest).

Airlines and flight crews as end users of the taxiway system are identified as 'Subjects' (high interest, low power). Their power in the taxiway system operation definitions and design is limited. They are mainly kept informed on changes and planned infrastructural works.

The ground handlers (users of the taxiway system for towing), as well as local residents represented by the ORS and regional authorities are identified as 'Crows' (low power, low interest): their opinion should be monitored, but they do not have an active role in setting the taxiway system.

In the end, both national and international authorities are identified as 'Context setters' (high power, low interest). They do not play an active role in the taxiway system, yet they set important regulations to which the taxiway system shall comply.

5.7 CONCLUSION

This chapter provides an introduction to Amsterdam Airport Schiphol (AAS), thereby answering Sub Questions (SQs) 6, 7, and 8. The gained insights on the airport's legacy, usage, characteristics, processes, procedures and stakeholders will be used to provide perspective in Chapter 6 by assessing the safety within the taxiway system of AAS.

6 SAFETY ANALYSIS OF THE TAXIWAY SYSTEM AT AMSTERDAM AIRPORT SCHIPHOL

In Chapter 4, four Key Performance Indicators (KPIs) were identified for taxiway systems: *safety, capacity, robustness* and *environmental impact*, as well as corresponding assessment methods. In this chapter, the taxiway system of Amsterdam Airport Schiphol (AAS) will be analyzed on the KPI *safety*. Due to time limitations, the taxiway system of AAS is not analyzed on the other identified KPIs. The focus for the safety KPI is based on its importance as described in Chapter 1: For AAS, the criterion as set my the Dutch Minister of Infrastructure and Water Management (2019a) that growth shall be demonstrable safely possible might cause difficulties, as elaborated in the report of the Dutch Safety Board (2017).

Hence, in this chapter, several analyses on the safety of AAS's taxiway system are performed, based on the in Section 4.3 defined assessment methods. However, two of the in Section 4.3 defined assessment methods were not performed: before analyzing a taxiway system on complexity, first further research on making complexity quantifiable is required. Also no analysis based on ground movement data was performed, since this data was not available for this research. Nonetheless, the following analyses are provided in this chapter: First, a heat map with traffic demand on nodes within the taxiway system is developed in Section 6.1. Second, deviations of Standards and Recommended Practices (SARPs) on the design of the taxiway system at AAS are discussed in Section 6.2. Third, in Section 6.3 problems as faced by interviewed stakeholders are discussed and evaluated. Fourth, occurrence reports and occurrence categories are discussed in Section 6.4. Fifth, in Section 6.5 a black spot analysis is performed. Sixth, in Section 6.6 a for taxiway systems new framework on safety was used: sustainable safety. The aim of sustainable safety is achieving safety by systematically reducing underlying risks of the traffic system with a focus on human factors (SWOV, 2018). Additionally, an overview of recommendations as provided by previous research on the airside safety of AAS (Hillestad et al., 1993; Dutch Safety Board, 2017) is discussed in Section 6.7. In the end, conclusions on the performance of the taxiway system at AAS on the safety KPI are provided in Section 6.8.

For the purpose of the different analyses, the taxiway system is defined as a node-link network model. In general, the nodes will be the main focus in this research. Therefore, all nodes are labeled. Taxiway/taxiway nodes are labeled by integers and taxiway/runway nodes are labeled by their name. Detailed maps with node labels are provided in Appendix G.

6.1 TRAFFIC INTENSITIES HEAT MAP

In order to put other analyses into perspective, insights are gathered on traffic intensities. Therefore, a heat map of traffic flows is created for annual movements per node. Unfortunately, historic data on traffic movements within the taxiway system of AAS was not available for this research. Accordingly, a stochastic model is developed in order to create the heat map. The stochastic model, including all made assumptions within the model, is included in Appendix G.

The generated heat map of AAS is shown in Figure 6.1. A number of things stand out in the heat map. The busiest areas appear to be around the central area (taxiways Alpha and Bravo), and taxiway Victor - to and from the Polderbaan. The high number of taxi movements on taxiway Victor can be explained by the high preference of usage of the Polderbaan (18R/36L) (Table 5.3). From the preferential runway configurations as mentioned in Section 5.3, it can also be distracted that the taxiways around the Oostbaan (04/22) are only used very little. Similarly, the small traffic demand to/from the Eastern threshold of the Buitenveldertbaan (27) can be explained by only being part of the fourth preferred runway configuration under good sight conditions.

Detailed heat maps, including labels containing the number of movements per node, are attached in Appendix H.

Figure 6.1: Heat map overview

In Figure 6.2, the heat map is zoomed in on the central area of AAS. In this zoomed version several things stand out:

- The busiest point within the taxiway system at AAS is the intersection of Rapid Exit Taxiway (RET) S4, taxiway Bravo and taxiway A4 (159,445 movements, see Figure H.2). The main traffic flows on this node are:
  - Traffic vacating runway 06 after landing via S4 (primary RET);
  - Arriving traffic from taxiway Quebec, taxiing towards the B-, C- or D-pier;
  - Departing traffic from the A-apron and B-pier routing towards runway 24 or North.

Figure 6.2: Heat map zoomed in on the central area of AAS

- All nodes around the threshold of runway 24 are crowded (see Figure H.3). In this area, many conflicting traffic flows may occur:
    - Traffic departing from runway 24, taxiing towards one of the entries from all directions;
    - Traffic departing from the A-apron, B- or C-pier taxiing to the North over taxiway Bravo;
    - Arriving traffic for the C/D-bay from all directions.
- Within the 'ring road' of taxiways, the traffic demand is relatively highest on taxiways Alpha en Bravo in the East and South-East (parallel to the Aalsmeerbaan and Kaagbaan). Next to the before mentioned traffic flow to/from the Kaagbaan (one of the primary runways), the high traffic demand can be explained by the type of traffic handled on aprons in this area: Narrow Body aircraft (NaBo). Since NaBo have smaller wingspans, generally more stands are located on a pier for NaBo. Moreover, turnaround times of NaBo are much smaller compared to Wide Body aircraft (WiBo), enabling more flights per gate per period of time. Hence, more flights are handled within bays with primarily NaBo stands (A-apron and B-, C- and D-pier).
- Amongst the very busiest nodes are also the Eastern and Western end-nodes of taxiway Quebec (144,048 and 149,606 annual movements respectively), showing the taxiway's importance within the taxiway system. Nevertheless, this high demand does not necessarily cause problems, since traffic flows on taxiway Quebec are generally uni-directional. Nonetheless, around the nodes conflicting traffic flows may occur.

  On the Eastern node ('Point Pieter'), the majority of traffic flows are either from taxiway Alpha to taxiway Quebec, or from taxiway Quebec to taxiway Bravo. Conflicting traffic on 'Point Pieter' generally takes place when next to the mentioned traffic flows a movement takes place to/from one of the Cargo aprons (Romeo and/or Sierra).

  For the Western node - close to the threshold of runway 36C - the primary flows are not as predefined as for the Eastern node. Four major traffic flows are: (1) to/from taxiway Quebec from/to taxiway Zulu, (2) to taxiway Quebec from taxiway Bravo, (3) to taxiway Alpha from taxiway Quebec, (4) to/from taxiway Zulu from/to taxiway Alpha. Conflicting traffic on this node generally takes place in case of of Southern-wind. In that case runway 18R is usually used for landings, with runway 18C as secondary runway for landings (see Table 5.3, preference 2). In this situation (18R and 18C used for landings), traffic which landed on runway 18R is routed via taxiway Zulu, to prevent for active runway crossings. Traffic towards the E-, F-, G- or H/M-piers from taxiway Zulu will continue via the Western node towards taxiway Alpha, where most traffic towards the A-apron and B-, C- and D-piers will taxi via Quebec. Similarly, traffic flows appear for traffic landed on runway 18C. Hence, both crossing and merging traffic flows may occur on the Western node.

6.2 STANDARDS COMPLIANCE

As mentioned before, the taxiway system at AAS is designed based on the *Certification Specification* as set out by EASA (2017), based on Standards and Recommended Practices (SARPs) of ICAO (2018a). The Certification Basis of AAS (Schiphol, 2018b) includes an overview of deviations from standards within the taxiway system at the airport. In general, deviations are classified as Equivalent Level of Safety (ELoS) or Special Condition (SC). Deviations that are not qualified as either ELoS or SC are put in the Deviation Acceptance and Action Document (DAAD), which have to be agreed by the airport authority and the Inspectie Leefomgeving & Transport (*Human Environment and Transport Inspectorate*) (ILT).

From the Certification Basis of AAS (Schiphol, 2018b), it can be concluded that on general the airport meets all certification specifications. Nonetheless, a number of deviations are listed:

1. Several taxiway curves do not comply with the requirement of 4m for the Outer Main Gear Wheel Span (OMGWS) clearance distance (ELoS);
2. Operations with code letter F aircraft using code E infrastructure are approved to use code letter E infrastructure: for taxiways a minimum distance of 49m between center line and object is applicable (ELoS);
3. At taxiway A1A, the longitudinal slope locally exceeds 1.5% (ELoS);
4. For several RETs a turn-off curve radius of less than 550m is used (ELoS);
5. The part of taxiway V serving as bridge over *Rijksweg A5* does not comply with item CS ADR-DSN.D.300(c) (DAAD);
6. At specific locations near the taxiway bridges on taxiways Q and V, the maximum allowable slope within the taxiway strip of 5% is exceeded (SC);
7. No runway-holding positions are present at taxiways C and D to protect the approach- and/or climb surfaces of runways 09 and 27 (ELoS);
8. The locations of the runway-holding positions on taxiways Y and Z do not comply with the requirement as set out in CS ADR-DSN.D.335(b)(1) (DAAD);
9. At taxiway A19, alternative colours (orange and blue) for taxiway center line markings of A19E and A19W are used (ELoS);
10. On various locations near taxiway-runway intersections, taxiway center line markings are interrupted in the curves, leading towards the respective runway(s) (DAAD);
11. On runway 09-27 between taxiways N2 and E6, the taxiway center line is marked over the total width of the runway. The same applies to the taxi route between taxiways S7W and S8, crossing runway 06-24 (SC);
12. The 'NO ENTRY' markings are singularly applied centered around the taxiway center line. At taxiways used by code E and F aircraft, these markings should be applied dually on both sides of the taxiway center line (ELoS).

Important deviations are published in the AIP The Netherlands (2019), such that they are easily accessible for flight crews. However, according to the Certification Basis, the following of the above listed deviations are *not* published: 3, 7 and 12. Besides, deviation 2 should be published in the Ground Movement Chart (AIP The Netherlands, 2019) of AAS (Schiphol, 2018b). However, not all parts of taxiways that are designed under the deviation are mapped on the Ground Movement Chart (e.g. taxiway A along the D-pier).

6.3 STAKEHOLDER FACED PROBLEMS

In this section, problems within the taxiway system at AAS as mentioned during the interviews by stakeholders are discussed. It should be noted that only interviewees with AAS stakeholders are considered in this section. Table 6.1 shows the twelve problems experienced and mentioned by concerned interviewed stakeholders.

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Apron Controller	Asset Manager 2	Asset Manager 3	Operations representative 1	Operations representative 3	Tow Truck driver	*TOTAL*
1. Often non-standard operation	✓	✓		✓	✓	✓		✓			6
2. Difficult area: taxiway system around threshold runway 24	✓		✓	✓	✓		✓		✓		6
3. Difficulty for rare visitors	✓	✓		✓			✓	✓	✓		6
4. Taxiways A/B very close to piers as ongoing taxi routes		✓		✓	✓		✓	✓			5
5. Missing vision on the taxiway system						✓	✓	✓	✓		4
6. Difficult area: taxiway system around threshold runway 36C	✓		✓				✓				3
7. Difficult area: 'Point Pieter'	✓						✓				2
8. Additional flows during de-icing (increases difficulty around 09/J-apron)					✓				✓		2
9. Often holding required due to limited number of stands		✓					✓				2
10. Tight around piers		✓			✓						2
11. Often changing traffic flows					✓						1
12. For towed traffic taxiway C redundant under 'Tower' control at runway 09										✓	1

Table 6.1: Identified problems at AAS per interviewee

6.3.1 Often non-standard operation

Throughout the interviews, pilots mentioned that AAS within Europe is one of the exceptional airports with an extensive use of standard taxi routes (directions), of which taxiways Alpha and Bravo are the most important. However, especially on Alpha and Bravo, 'Ground'-control regularly often deviates from the defined directions - of which the pilots are sure that there always is a good reasoning for doing so. To a large extend, this can be explained by the gap of Air Traffic Control (ATC) being a service provider on the one hand, trying to satisfy all users, and being responsible for a good and safe flow of traffic on the other hand. Nonetheless, Albright (2017) searches his own conscience: *"We often find ourselves having to adjust, reorder or even skip some standard operating procedures because they don't exactly fit the situation at hand, they would take more time than a widely accepted shortcut, or we think we have a better method. Operating ad hoc, in the heat of the moment, we risk not carefully considering all possible factors."*

Some examples of areas at AAS where defined directions are deviated from regularly are provided by the interviewed pilots:

- "In case of a departure out of gate D5, the defined taxi-route towards runway 18L is via A13, N2, crossing runway 27 and continuing towards the threshold of 18L. However, it might be the case that already two aircraft with the same Standard Instrument Departure route (SID) are waiting for line-up. Since two aircraft with the same SID require greater separation (decreasing capacity), they prefer not to let these two aircraft takeoff after each other. In that case, they might ask me to enter runway 18L via entry E5, to takeoff in between the other two aircraft. If you get this question while taxiing on A13 close to gate E24, you should actually go non-standard against the defined direction via taxiway Bravo towards E5, or via A12, Bravo and making a right-turn towards E5. However, ATC generally won't do that, they will direct us via the Papa-(holding) apron, actually no part of the taxiway system. Hence, they deviate from the procedure in that case." (Pilot 1).

- "If I arrive on taxiway Alpha from the West (e.g. landed on runway 18C or 18L) and my allocated stand is D5, the defined taxi-route (based on defined directions) is via A10. However, often while passing the E-pier, ATC says 'Entering via A13 approved'. In that case I can make a right-turn immediately and do not make the defined de-tour, yet, making it non-standard." (Pilot 1)

- "Along the Zwanenburgbaan, directions of taxiways Alpha and Bravo are often ignored. Especially for Alpha, since it enables you to taxi directly onto taxiway Zulu for going towards the Polderbaan." (Pilot 2).

- "While taxiing on taxiway Alpha in Eastern direction (confirm defined directions), ATC regularly gives the instruction to switch to taxiway Bravo for some sections, in case an aircraft is being push-backed at the F-pier." (Pilot 4)

Both amongst pilots and airport representatives, it is recognized that this might cause safety risks. Since the operation often deviates from procedures, pilots are inclined to make the deviation a habit. Therefore, Operations representative 1 wonders whether it would be better to make the alternative the new standard or to abolish certain procedures in order to increase alertness of flight crews for the instructions of ATC.

6.3.2 Difficult area: taxiway system around threshold runway 24

The most mentioned difficult area within the taxiway system at AAS is around the threshold of runway 24. It should be noted that this area currently is not a formal hot spot. As explored in Section 6.1, this also is one of the most crowded areas with many conflicting traffic flows; through traffic on Alpha and Bravo, traffic from all directions towards the threshold of runway 24 for takeoff, or traffic that vacated runway 06. Besides, aircraft that received an instruction to 'Hold Short runway 24' often stop at the category 3 holding or stop at a large distance from the category 1 holding, resulting in their tail blocking runway Bravo, disabling ongoing traffic on taxiway Bravo. Therefore, traffic landed on runway 18L or 18C routed via Quebec which is often directed against defined directions over taxiway Alpha, because of these spatial deficits around Alpha 8. Hence, this can be seen as one of the most complex intersections, with regular congestion. The area is crucial within the taxiway system, also making the planning of maintenance challenging, Asset Manager 3 mentions.

Moreover, the borders of both ATC's 'Ground'-control areas and AAS's 'Apron'-control are located within this area: the border is located East-West at the Southern pier of the D-pier (around A9). This makes the area even more complex, users state. Pilot 1 mentions that it is understandable that it is well for ATC, but workload increasing for pilots, and thus undesirable. Pilot 3 refers to another difficulty of this location of the 'Ground'-control border: *"On the landing charts, for all landings on runway 36R, 121.805Hz was mentioned as 'Ground'-frequency, to which we should switch automatically (without instruction). However, by vacating runway 36R via E1 (which most narrowbody aircraft do), you enter the 'Ground'-area of 121.705Hz, since the border is North of E1. In that case the first and only instruction of 121.805Hz was to switch to 121.705Hz. Since a few mothns, ATC solved this issue: now during approach 'Tower'-control instructs to contact 'Ground' on 121.705Hz in case of vacating the runway via E1."* Also the interviewed Apron Controller recognizes difficulties for this location of the border of 'Apron'-control's North and South area.

6.3.3 Difficulty for rare visitors

Where the Dutch Safety Board (2017) calls AAS' taxiway system 'complex', most stakeholders do not necessarily experience it as such. Pilots mentioned that for flight crews who are used to the system, the standard taxi routes and large number of possible routes, it is rather simple. However, they can imagine that for flight crews who visit the airport for the first time (or rarely), it might be very challenging. For example Pilot 1 understands that foreign pilots sometimes are lost in the taxiway system and do not know what is expected from them. Similarly, Pilot 2 refers to the difficulty of standard taxi routes for rare visitors: "Those standard routes are defined in a separate book. You have to get used to it. I can imagine that a foreigner visiting Schiphol, who did not want to read every detail, is scared when he only receives a very limiting taxi instruction." Also Operations representative 1 mentions that within the operations department, they often get the feedback that non-AAS based carriers have more difficulties resulting them in stopping more often and requiring more communication with 'Ground'-control. Operations representative 1: "As airport we have to ensure that also those pilots, who visit AAS for the first time, are able to find their way or get the right supervision, in order to prevent them from taking a wrong turn or taking off from a taxiway."

Contrary, Operations representative 3 notices that most incidents happen with home-carriers, which he explains by the assumption that non-AAS based crews are probably more alert. Nonetheless, Operations representative 3 recognizes that amongst foreign carriers, the English communication causes problems, resulting in confusion. In the end, he presumes that most (relatively) small occurrences concern foreign carriers, where serious incidents mostly concern AAS-based airlines.

6.3.4 Taxiways A/B very close to piers as ongoing taxi routes

Due to the layout of AAS, taxiways Alpha and Bravo are located relatively close to all piers. Several interviewees mentioned this as a downside, since it requires extra high attention along the large number of intersection. Also the interviewed Apron Controller prefers ongoing routes to be located further away from terminal buildings, to provide more space for movements close to buildings and pushbacks.

6.3.5 Missing vision on the taxiway system

All interviewed representatives of Royal Schiphol Group (AAS) referred to the high quantity of infrastructure at the airport; too much from their point of view. Asset Manager 3 mentions that LVNL "prefers everything to be possible (maximum flexibility), where for the airport it should be safe with good accessibility". Therefore, the airport (e.g.) prefers not too much short taxiways connectors, since those do not increase safety but do increase complexity. Asset Manager 2 refers to the rail-network in The Netherlands, which is being simplified. He thinks a similar approach should be followed in the taxiway system at AAS: "It probably decreases the flexibility, but it makes the system more safe and sound." According to Asset Manager 2 and Operations representative 1, AAS is lacking a vision on this trade-off: should the airport aim for simplification, or for flexibility? Therefore they argue for a company-strategy on how to use the taxiway system, preferably together with LVNL. Besides, they suggest a maintenance strategy of the taxiway system, which already exists for the runways. Operations representative 1: "In the maintenance strategy of runways, it is stated that at maximum one runway is allowed to be closed for maintenance at a time. I think it would be good to have a similar parameter for the taxiway system. Although, I can imagine that in the taxiway system you do not concern a specific link, but rather nodes/intersections which are critical." Recently, Royal Schiphol Group initiated a project on defining a taxiway maintenance strategy.

6.3.6 Difficult area: taxiway system around threshold runway 36C

Another difficult area can be found around the threshold of runway 36C, where taxiways A, B, Q and Z merge. As mentioned in Section 6.1, this Western end-node of taxiway Q has a high traffic demand with many conflicting traffic flows. This is also recognized by pilots. Besides, Asset Manager 3 points out that the complexity of this area further increases by building the parallel Quebec taxiway (as mentioned in Section 5.4). Pilot 1 explains the risks in this area: "Especially when both 18C and 18R are used for landings, the risk in this area increases. For example, in case both traffic landed on runway 18R arrives at this spot, and other traffic that vacated 18C at w7/W8, both heading for taxiway Q; who goes first in that case? Sometimes 'Ground'-control provides an instruction, but not always. Every now and then this even results in a bit of racing to be first. It gets even more dangerous in case the traffic coming from taxiway Z goes to the North, onto taxiway A. In that case both traffic flows actually cross. The route from 18C and A slightly converge, although this is not clearly visible on the map. Hence, in case (after landing on 18C) you stop too far on A26 for crossing onto Q, you easily assume to have enough separation to traffic from Zulu. However, this aircraft comes awfully close, since Z/A converges towards A26. Moreover, aircraft coming from Zulu generally taxi with high speeds, since there is an upward slope. For departing traffic from 36C entry W10 is difficult in case the taxi route originates from taxiway Q. From Q you easily take the first left-turn onto Z instead of W10, disabling direct access to the runway." (Pilot 1)

6.3.7 Difficult area: 'Point Pieter'

'Point Pieter', also referred to as taxiway Quebec's Easter end-node, is mentioned as difficult area in the taxiway system, with many different and potential conflicting traffic flows. Besides, at this intersection direct access is possible to S2; a high energy crossing with runway 06/24. The intersection becomes even more complex once the parallel Quebec taxiway will be opened, and therefore requires additional attention.

6.3.8 Additional flows during de-icing (increases difficulty around 09/J-apron)

As mentioned in Section 5.3.5, de-icing at AAS can be executed either at the gate or at a remote location. The latter case causes additional traffic movements of aircraft taxiing to/from the de-icing apron. Since AAS is setting up a project for more central de-icing locations (to reduce aircraft stand occupancy time), this traffic demand will further increase. Operations representative 3 points to the area around the J-apron (used as de-icing apron) and the threshold of runway 09. During de-icing, many movements take place in the area, causing conflicting traffic flows, especially in case runway 09 is used for takeoffs or during a large demand of towed traffic to/from the Uniform buffer aprons.

6.3.9 Often holding required due to limited number of stands

Within the operation, arrival times of aircraft can have large variations, especially for long-haul flights. This might result in the situation that the assigned stand for a flight is not (yet) available (and also no other). Asset Manager 3 refers to a number of solutions for this situation: "The first option is the remote holdings. However, these are not sufficient currently. Therefore, aircraft might have to wait on taxiways, causing implications for the whole system since other traffic flows are blocked."

Also Pilot 2 underpins the shortage of aircraft stands for handling flights at AAS: "Where the outbound flow at AAS is organized perfectly -generally you can taxi from gate to runway in one smooth flow without stopping- thanks to the introduction of Collaborative Decision Making (CDM), the inbound flow often causes issues. Due to a lack of gates, we often have to wait on taxiways for our gate to become available."

6.3.10 Tight around piers

Both Pilot 2 and the Apron Controller underpin the difficulties of the pier-structure of AAS. Pilot 2: "Around the piers is actually the most difficult part of taxiing at AAS. It is very crowded with many aircraft movements and there is not much space. In case a first aircraft is being pushbacked, another second aircraft generally has to wait until the first aircraft has left the bay."

6.3.11 Often changing traffic flows

One of the concerns found by the Dutch Safety Board (2017) is confirmed by users: in an international context (Table 6.2), the number of runway configuration changes related to noise at AAS are extremely high. On average, the runway configuration changes in total 18 times per day, of which 16 are related to noise regulations (Dutch Safety Board, 2017). As explained in Section 5.3.2, the usage of runway configurations is subject to several factors: weather (wind and sight), (noise) regulations and defined preferential runway configurations. As ATC-provider, Air Traffic Control the Netherlands (LVNL) determines which runway configuration is used. In the report by the Dutch Safety Board (2017), LVNL states that of the 18 runway configuration changes per day, on average 90% (16 changes) are based on noise regulated preferences and 10% (2 changes) based on (changed) meteorological circumstances.

Airport	*Number of runways*	*Number of runway configuration changes (daily)*
New York JFK	4	0-1
London Heathrow	2	1
Chicago O'Hare	8	1
Frankfurt	4	0-1
Munich	2	1
Singapore Changi	2	0-1
AAS	**6**	**16**

Table 6.2: Average number of daily runway configuration changes in relation to noise (Dutch Safety Board, 2017)

The Dutch Safety Board (2017) focuses on safety complications for runway incursions due to the high number of runway configuration changes, where interviewees also point to risks in the taxiway system. A change in runway configuration causes a change in traffic flows in the taxiway system too. Since there are a lot of runway configurations possible at AAS due to the large number of runways, there are also a lot of traffic flows possible in the taxiway system - there is a large number of Origin-Destination pairs between gates and runways, with additional dependency of usage of other runways. The changes in traffic flows within the taxiway system might lead to conflicting flows. Besides, the predictability of the taxi process decreases. As mentioned before, rare visitors already seem to experience challenges on taxi process under normal conditions. Hence, a situation with changing taxi routes - thereby decreasing the predictability of the taxi process - might cause risks for rare visitors in particular.

In the end, two things can be concluded on this subject. Firstly, a contradiction can be seen in relation to runway configurations: on the one hand 90% of runway configuration changes are due to regulations of the Dutch government in relation to noise. On the other hand the Dutch government requires AAS to follow up recommendations of the Dutch Safety Board (2017) including reducing the daily number of runway configuration changes. Secondly, it should be acknowledged that runway configuration changes not only impact the safety around runways, but also within the taxiway system due to changes traffic flows.

6.3.12 Towed traffic taxiway C redundant under 'Tower' control at runway 09

The interviewed tow truck driver only mentioned one point of improvement from his point of view. In general, towed traffic is under guidance of 'Apron'-control, except for runway crossings, which are controlled by 'Tower'-control. However, there is one other location: at taxiway Charlie, along the threshold of runway 09, which is also under control of 'Tower'-control. Tow truck driver: "I really think this area could easily be under supervision of 'Arpon'-control as long as runway 09/27 is not active. The link is very short and you do not cross the runway itself. Remaining it under 'Apron'-control would make it easier and decrease confusion and work load."

6.4 OCCURRENCE REPORTS

As mentioned in Section 2.6, occurrence report data was obtained from the ILT. The data set contains occurrence reports related to AAS between 1 January 2009 and 31 September 2019. After preparing the data set as described in Section 2.6.2[1], the data set contained 1,766 occurrence reports:

- 0 classified as *Accident*
- 1,281 classified as *Incident*[2]
- 0 classified as *Serious incident*
- 2 classified as *Major incident*
- 45 classified as *Significant incident*
- 43 classified as *Occurrence without safety effect*
- 112 classified as *Observation*
- 283 classified as *Not determined*

In the time period of the data set, AAS handled 4,387,261 movements (Royal Schiphol Group, 2019b). Hence, during the past decade, on average there was one occurrence per 2,711 movements, or 3.7 occurrences per 10,000 movements at AAS. Figure 6.3 shows the number of annual[3] occurrences and the number of movements.

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[1] It should be noted that runway incursions are not taken into account in this analysis, since runways are not part of the scope of this thesis research. Moreover, runway incursions are a considered to be a separate topic of study (e.g. Koopmans (2019)).

[2] Unfortunately, the 1,281 occurrences classified as *incident* are not classified as one of the five specific incident categories.

[3] For 2019, the set only contains reports up to and including September.

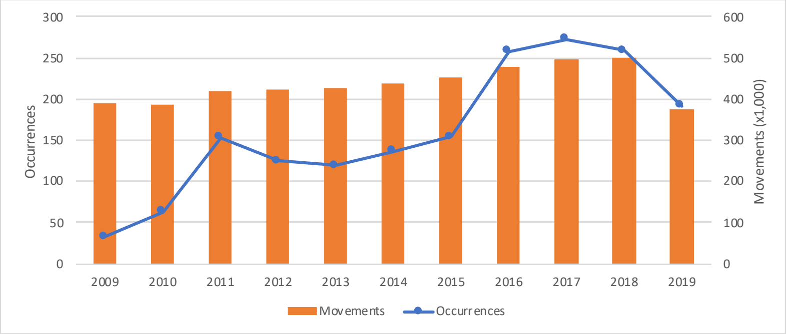

Figure 6.3: Number of occurrences in the taxiway system at AAS and number of movements

Since the number of movements has not been constant over the past decade, and to account for the incompleteness of the 2019 data, Figure 6.4 shows the number of occurrences per 10,000 movements.

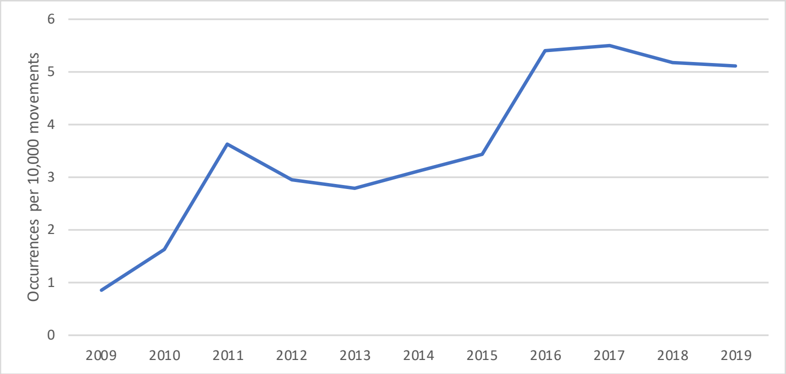

Figure 6.4: Number of occurrences per 10,000 movements

Figure 6.4 shows an increasing trend in occurrences per 10,000 movements. Over the past decade, the number of occurrence reports per 10,000 movements increased by 505%. However, the occurrence report data does not permit any definite conclusions to be drawn on number of occurrences, since legislation on reporting and reporting behaviour has changed over the years (Van der Wal, 2019): The reporting regulations by the European Union (2014) are implemented by the National organizations between 2014 and 2017. Hence, it is likely that the increase in occurrence reports in this period is primarily caused by the tightened regulations. After 2016, there seems to be a stabilization in number of occurrence reports.

6.4.1 Occurrence categories

Based on the occurrence report data, an analysis is performed on types of occurrences. As mentioned in Section 2.6.2, the following categories are defined for analysis:

1. ***ATC***: Deviation from standard procedures by ATC;
2. ***Lacking ATC***: Guidance of ATC is lacking;
3. ***Flight Crew***: The flight crew deviates from the instruction of ATC or a standard procedure;
4. ***Other vehicle***: An occurrence of an aircraft with another vehicle (no aircraft), e.g. tow movements on taxiways or service vehicle or ambulances on intersections of taxiways with service roads;

5. ***Failure***: A failure within the taxiway system, such as FOD;
6. ***Taxi speed***: The flight crew exceeds the allowed taxi speed.

Figure 6.5 shows the absolute number of occurrence reports split per category, including the shares per category. It can be seen that the majority of reports (on average $> 50\%$) regards deviations from instructions of ATC or from standard procedures by *flight crews*. Thereafter, the major contributing category (on average 27%) regards occurrences of aircraft with *other vehicles*.

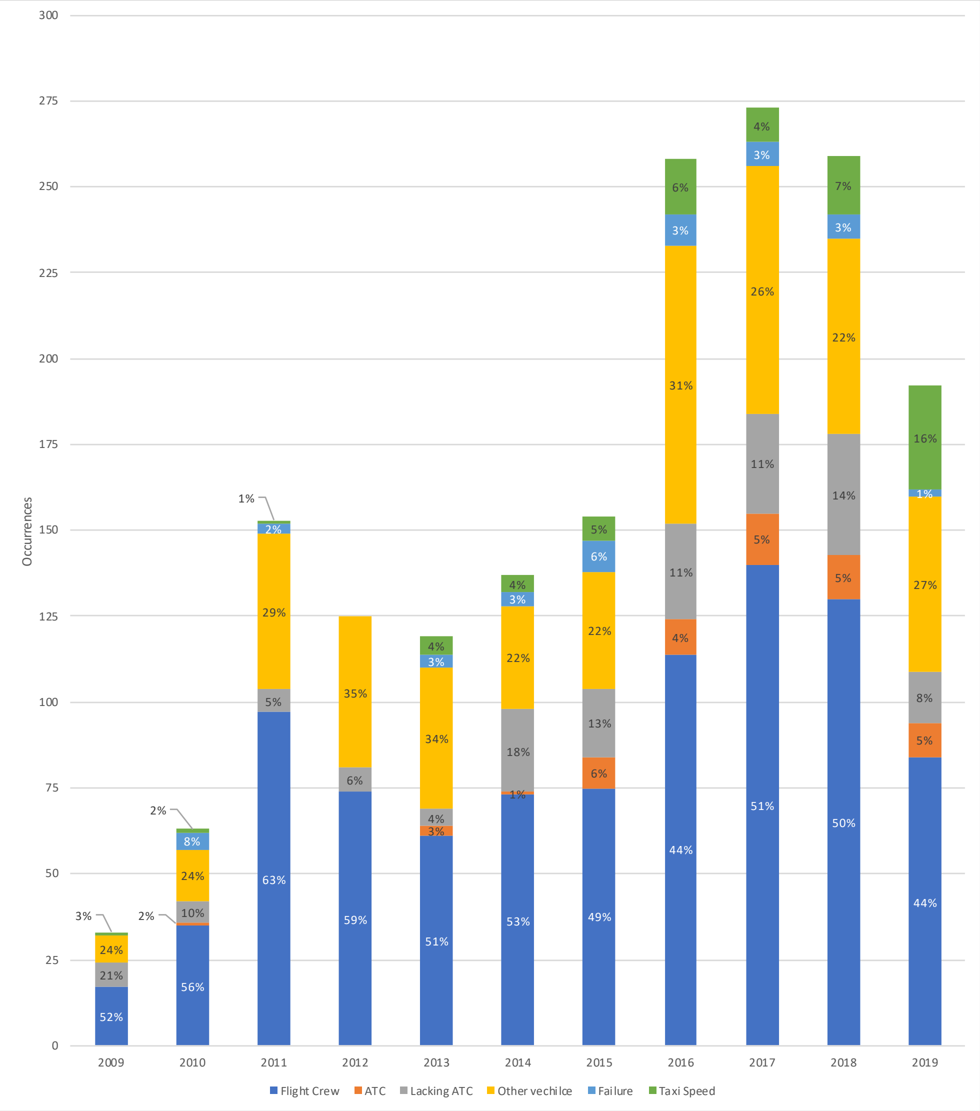

Figure 6.5: Annual occurrence reports per identified occurrence category

In order to gain insights on an eventual increase or decreases of number of occurrence reports per category, Figure 6.6 shows for each of the occurrence categories per 10,000 movements the occurrence index, with 2009 being 1.0. A number of things stand out in Figure 6.6: The number of *failures* remained rather constant, which seems reasonable, since the number of failures (e.g. Foreign Object Debris (FOD)) can be assumed to be independent of number of movements. Besides, the number of deviations by *ATC* shows an increasing trend, suggesting that ATC more often deviates from standard procedures in the operation. Moreover, a large increase of number of occurrence reports on *taxi speed* exceeding can be seen. As stated by Pilot 3, speed exceeding is increasingly monitored at some airlines. Hence, the increase of reports on speed exceeding might be (partly) caused by the increasing surveillance. Notwithstanding, amongst the 93 reports on exceeding the taxi speed, several causes can be found. Of these reports, 14 speed exceedances were performed by the flight crew on request of ATC. Three reported reasons for this request are (1) in order to let the aircraft overtake a preceding aircraft to adjust the planned departure sequence, (2) expediting in order to cross runway 18C/36C at intersection W5 before the runway is opened, or (3) to expedite vacating a runway after landing because of another runway on short final, which is also recognized by interviewed pilots. Five conscious speed exceedances were on request of the flight crew, primarily based on the pressure of arriving on time and meeting the schedule. In the end, the majority of exceedances (74) were unconsciously caused by the flight crews and only were momentary. Several explanations are reported: distracted by non-standard/confusing ATC instruction, tail wind/light aircraft, going downhill, fatigue and accidentally being inattentive (e.g. due to being in a conversation, paying attention to birds around the aircraft). Nonetheless, as mentioned before, the occurrence report data does not permit any definite conclusions to be drawn on number of occurrences, since legislation on reporting and reporting behaviour has changed over the years (Van der Wal, 2019).

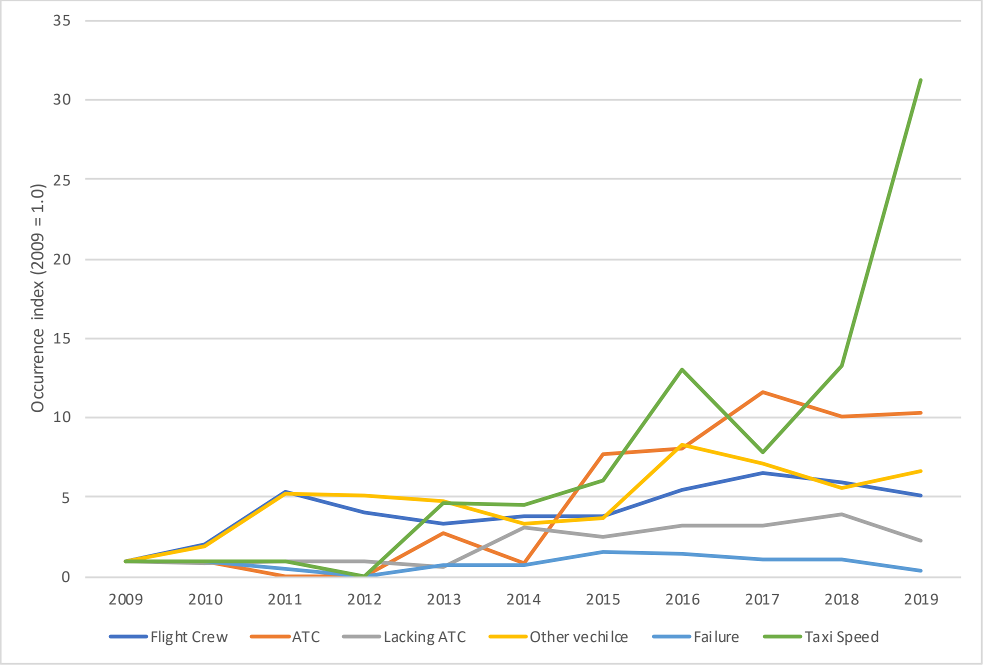

Figure 6.6: Normalized number of occurrences per 10,000 movements per category

6.4.2 Investigated incidents

In the past decade, three incidents have been investigated by the Dutch Safety Board (2011, 2019a, 2019b). The first two incidents underpin difficulties around taxiway A26 in-between the threshold of runway 36C and the Western end-node of taxiway Q, where the third incident shows the risk of regularly operating non-standard. Below, these occurrences are briefly described.

Takeoff from taxiway (10 February 2010)

In 2010, the complexity of the taxiway system at AAS resulted in a takeoff from a taxiway (Dutch Safety Board, 2011). Two aircraft were involved in the incident: a Boeing 747 and a Boeing 737. At a taxiway intersection A27 (Western end-node of taxiway Q), the Boeing 747 flight crew was confused and stopped taxiing: they taxied in Southern direction towards W10 to enter runway 36C. Simultaneously, ATC gave the Boeing 737 clearance to enter the runway (non-standards) via RET W8. Due to the error of the Boeing 747 flight crew, additional communication with the ATC was needed. This lead to confusion of the Boeing 737 flight crew to their own maneuvering, resulting in lining up on a taxiway instead of the Runway (Dutch Safety Board, 2011). During the Boeing 737's takeoff, the aircraft passed by another taxiing aircraft at only several meters.

Near collision (2 February 2019)

The crew of an Airbus A320 (on taxiway Alpha/A26) was instructed to give priority to another Airbus A320, which was approaching from the right, from taxiway Zulu. However, the crew did not observe this approaching aircraft in the dark, which forced the crew of this aircraft to make an emergency stop. The crew of the stopped A320 stated that the right wing tip of the other A320 passed at a short distance from their cockpit (Dutch Safety Board, 2019a). However, the investigation of the Dutch Safety Board on this occurrence is still ongoing. This incident is in line with the problems of the Western end-node of taxiway Quebec as described by Pilot 1.

Takeoff from taxiway (6 September 2019)

A Boeing 737 taxied in Northern direction on taxiway Charlie towards the threshold of runway 18C (there is no standard direction for taxiways C and/or D, however, generally traffic towards runway 18C is directed over taxiway D) when it received clearance to takeoff from runway 18C (Dutch Safety Board, 2019b). The flight crew then made a left-turn and turned onto taxiway Delta instead of runway 18C (by making a direct 180 degrees turn, which generally when taxiing via taxiway D results in lining up on runway 18C). From there, they started the takeoff in Southern direction on taxiway Delta. ATC noticed the initiated takeoff at the taxiway and instructed the crew to stop immediately. The flight crew aborted the takeoff and taxied back to the beginning of runway 18C. After receiving takeoff clearance or the second time, the aircraft took off uneventfully.

6.5 BLACK SPOT ANALYSIS

On the (remaining) set of occurrence reports, a black spot analysis was performed. Table 6.3 shows the number of occurrence reports per taxiway. Unfortunately, 846 of the 1,766 occurrence reports did not contain a location indication. Next, black zones are defined in order to better map occurrences. Black zones were used since in a large part of the taxiway system (especially along taxiways Alpha and Bravo) intersections are located close to each other. As defined by Geurts and Wets (2003), black zones are useful to explore sets of contiguous spatial units taken together, characterized by a high number of accidents. The following black zones were identified:

- A1, A2
- A4, S4
- A5, A6, A7, S5, S6
- A8, S7, E1
- A10, A11, A12, E2, E3, E4
- A13, N2, E5, E6
- P1, P2, P3
- A14, A15, A16, N3
- A18, A18, N4
- A19 (E/C/W)
- A21, A22, W6
- A24, W7
- A26, W10
- G1, G2
- V1, V2
- V3, V4

Taxiway	#	*Taxiway*	#	*Taxiway*	#
A	56	A9	13	S1	4
A1	17	B	48	S2	6
A10	16	C	12	S3	7
A11	1	D	2	S4	4
A12	20	E1	9	S5	13
A13	33	E2	9	S6	11
A14	13	E3	7	S7	29
A15	3	E4	7	V	10
A16	13	E5	9	V1	4
A17	13	E6	3	V2	2
A18	3	G	23	V3	18
A19	26	G1	70	V4	5
A2	19	G2	20	W1	1
A20	9	G3	1	W10	2
A21	13	G4	4	W11	7
A22	3	G5	5	W2	1
A24	1	N1	1	W3	1
A25	3	N2	34	W4	2
A26	14	N3	16	W5	21
A3	22	N4	5	W6	6
A4	25	P1	3	W7	6
A5	15	P2	1	Y	6
A6	15	P3	2	Z	22
A7	8	Q	5	'Point Pieter'	17
A8	45				

Table 6.3: Overview of number of occurrences per taxiway

From Table 6.3, it can be concluded that most occurrences are reported along taxiway Alpha (all A-taxiways). Unfortunately, 56 occurrences on taxiway Alpha are not specified in location, as well as 48 occurrences along taxiway Bravo. Occurrences on taxiways Alpha and Bravo are not used in the black spot analysis: their extensive length would make it nonsense to plot a black spot on a specific location.

Besides, it can be concluded that the highest number occurrences are reported in relation to taxiway G1, in the General Aviation (GA)-area of AAS. However, since only 'handelsverkeer' is considered in this study (excluding GA-traffic), no further analysis on this area will be performed. Moreover, from the heat map analysis, it can be concluded that commercial traffic hardly operates in this area.

Figure 6.7 shows the black spots and black zones of the taxiway system of AAS, from which several things can be concluded. Firstly, the largest black zones appear to be the area close to the threshold of runway 24, which also was identified as one of the busiest areas before. Secondly, a high number of occurrences are reported in the North-East area of taxiways Alpha and Bravo. In this 'corner' of AAS's central area a lot of runway exits/entries are situated close to each other, of two different runways. Besides, the major remote holding apron is located in the middle of the area, as well as the D/E (NaBo and WiBo)- and E/F-bays (WiBo). When looking at Table 6.3, it can be seen that primarily taxiways A13 and N2 (which crosses runway 09/27) contribute to the high number of occurrences in this black zone. This area is defined as hot spot. Thirdly, it can be concluded that in the Southern area of taxiways Alpha and Bravo along the regionals-apron, although it is the area with the highest traffic demand, the number of reported occurrences is relatively low.

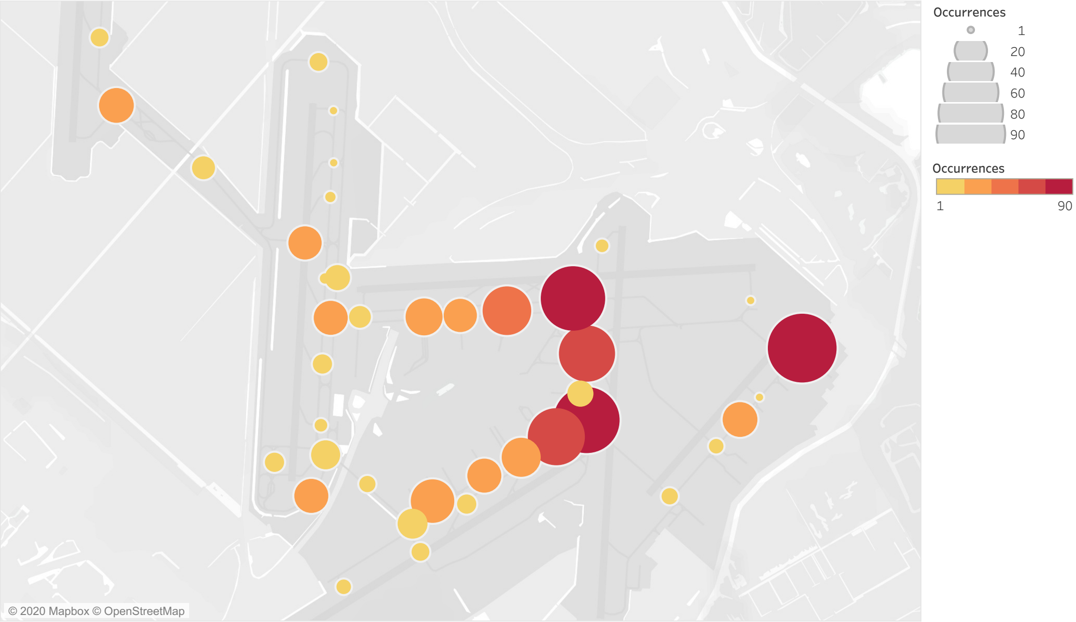

Figure 6.7: Black spots and zones of the taxiway system at AAS

To gain more insights on occurrences in the major black zones, word clouds are created for those areas. Hence, first a word cloud is created for the two black zones around the threshold of runway 24 together (taxiways A5, A6, A7, A8, E1, S5, S6, S7). In Figure 6.8, a few words stand out: *give way*, *runway*, *instead* and *vacating*. These words suggest that major occurrences are related to giving way to each other and vacating runways, probably associated to the in Section 5.4 described separation procedures at AAS. Moreover, vacating runways was mentioned before: ATC might request flight crews to exceed taxi speed limits in order to expedite their runway-vacating because of successively aircraft on short final. Therefore, it is recommended to perform more research on the following up of giving way by pilots to traffic from the right and vacating runways and eventual interference of ATC in this.

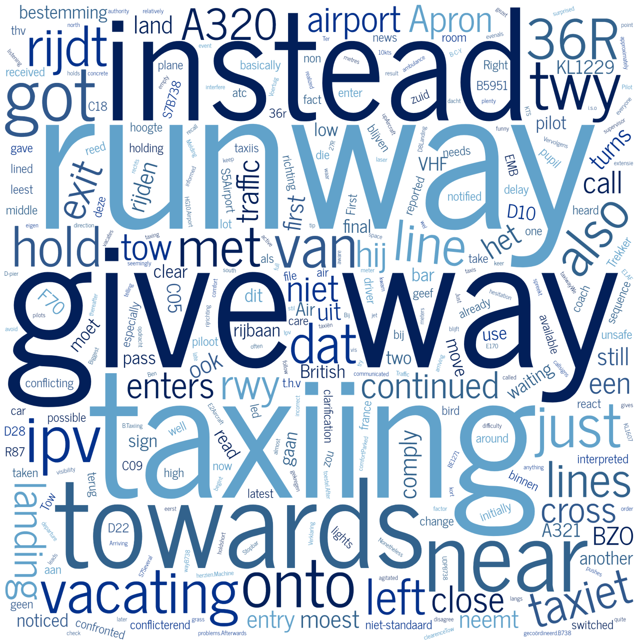

Figure 6.8: Word cloud on the occurrence reports for taxiways A5, A6, A7, A8, E1, S5, S6, S7

Also a word cloud is created for the North-East area of taxiways Alpha and Bravo (taxiways A13, E5, E6, N2). In the word cloud in Figure 6.9 the following words stand out: *A13* (which is one of the major locations in the area), *deviates*, *18L* and *naar/towards*. These words suggest that major occurrences are related to taxiing towards runway 18L from taxiway A13, which was also one of the by Pilot 1 mentioned examples. Besides, the fact that both *naar* and *towards* pop up in the word cloud, also shows the vulnerability of the occurrence report data set, since reports are both in English and Dutch, making (automatic) analysis through word processors rather difficult.

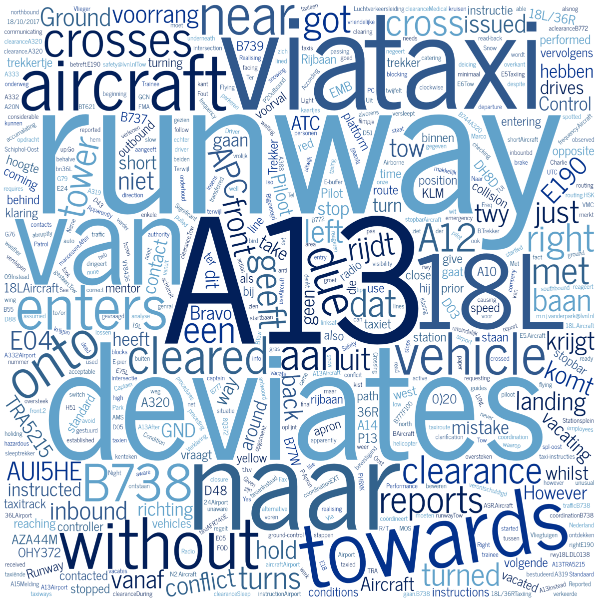

Figure 6.9: Word cloud on the occurrence reports for taxiways A13, E5, E6 and N2

6.6 SUSTAINABLE SAFETY

As mentioned in Section 4.3, assessing a taxiway system on sustainable safety as defined by SWOV (2018) has not been done before, although taxiway systems show similarities to road systems. The aim of sustainable safety is achieving safety by systematically reducing underlying risks of the traffic system through technical and organizational principles, with a focus on human factors (SWOV, 2018). This is in line with the by ICAO (2018b) defined approaches to safety within the aviation industry. In this section, the taxiway system of AAS is assessed on the principles of sustainable safety, as described in Section 4.2.

6.6.1 Functionality

According to the functionality design principle, a network should have an hierarchical and functional structure. In taxiway systems, this is split up in two major categories (Section 3.3): *taxiways* (intended to provide links on the aerodrome; flow function) and *aircraft stand taxilanes* (intended to provide access to aircraft stands only; exchange function). Both categories have slightly different design criteria, in which the separation distances are the major difference (see Section 3.5). The differences are based on the assumption that on aircraft stand taxilanes, flight crews are more focused since within a short time they will access an aircraft stand and therefore the aircraft's speed is lower as well.

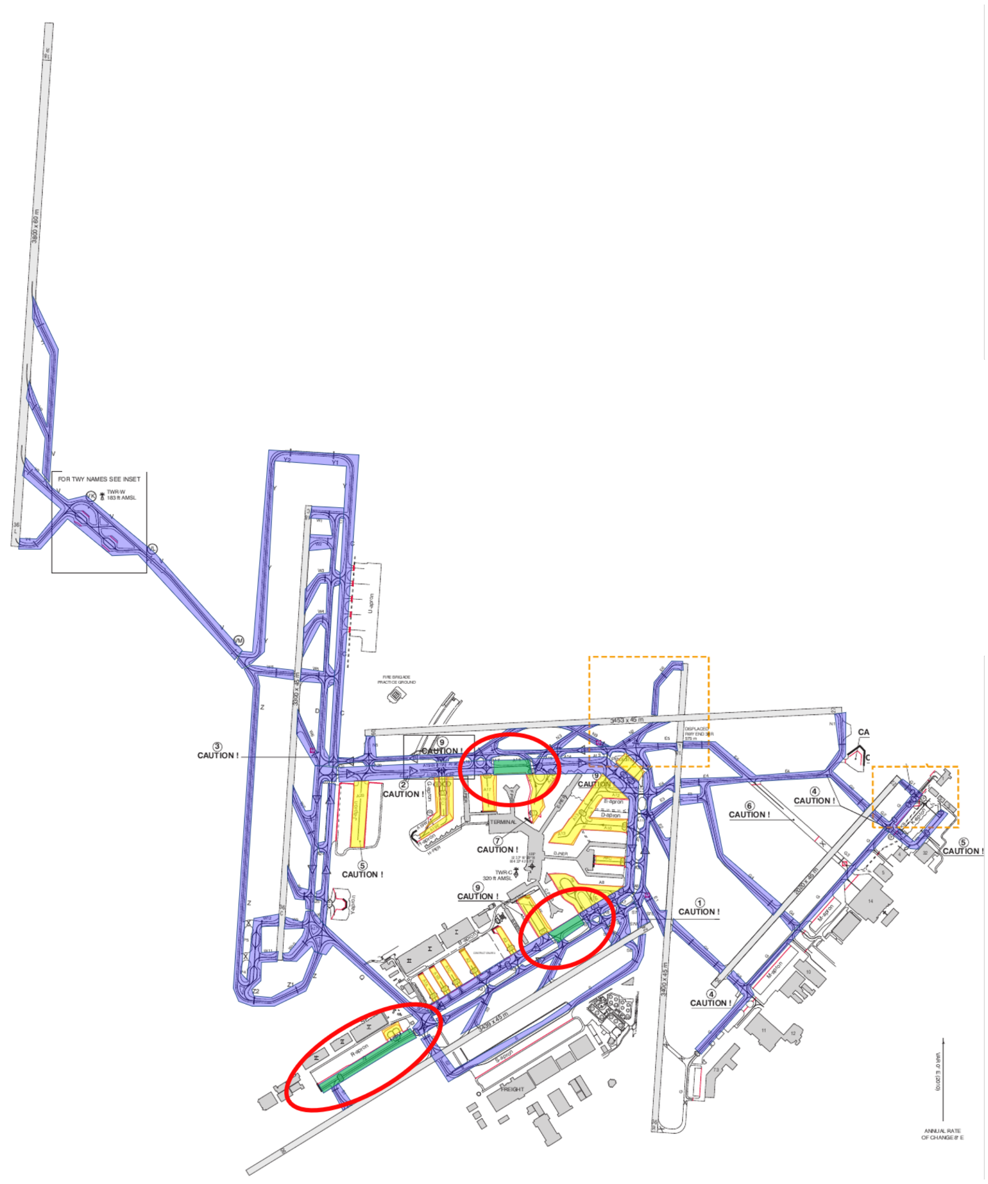

Figure 6.10: Taxiways (blue), Apron taxiways (green, red circled) and Aircraft Stand Taxilanes (yellow) at AAS

Figure 6.10 shows which of the separation distances are used within the taxiway system at AAS. The separation distances are measured in AAS-drawings and based on the maximum allowed aircraft wingspan as published in AIP The Netherlands (2019) and taking deviation 2 of the before mentioned deviations from certification specifications into consideration. It can be seen that all bays around piers at AAS are designed by using *taxilane clearances* and all other taxiways using *taxiway clearances*. However, next to these two categories, 'grey roads' (SWOV, 2018) might be identified: *apron taxiways*, which provide both through taxi-routes as well as access to aircraft stands. Yet, distinguishing apron taxiways and aircraft stand taxilanes is debatable since no strict definition is provided on through taxi-routes. Nonetheless, Figure 6.10 shows the clearly identified apron taxiways at AAS: they are designed with taxiway clearances, but also provide access to stands.

Two debatable apron taxiways are shown in Figure 6.11. These examples suggest that for the sake of handling peaks in traffic demand, the 'greyness' of the definition is being utilized, undervaluing the impact on safety. Within the left red circle, taxiways A19E and A19W are shown as apron taxiway. These taxiways are primarily used by NaBo aircraft to and from the H/M-pier, where taxiway A19C is used by WiBo aircraft for access to G-stands. Hence, along the G-pier, taxiways A19E and A19W provide a through-route to the H/M-pier and taxi speeds might be expected to be relatively high for taxilanes (as which they are currently designed). For comparison; a similar situation can be found at Munich Airport (taxiways for either two NaBo or one WiBo). However, at the German airport taxiway clearances are used.

Within the right red circle in Figure 6.11, taxiways A10 and A13 are shown as apron taxiway, although this situation is even more debatable and questionable than the above described situation at taxiway A19: the taxiways are primarily used for accessing stands, however the length of the bay is relatively extensive, causing pilots to taxi at relatively high speeds if they are going to/coming from a stand at the end of the bay (according to the interviewed pilots).

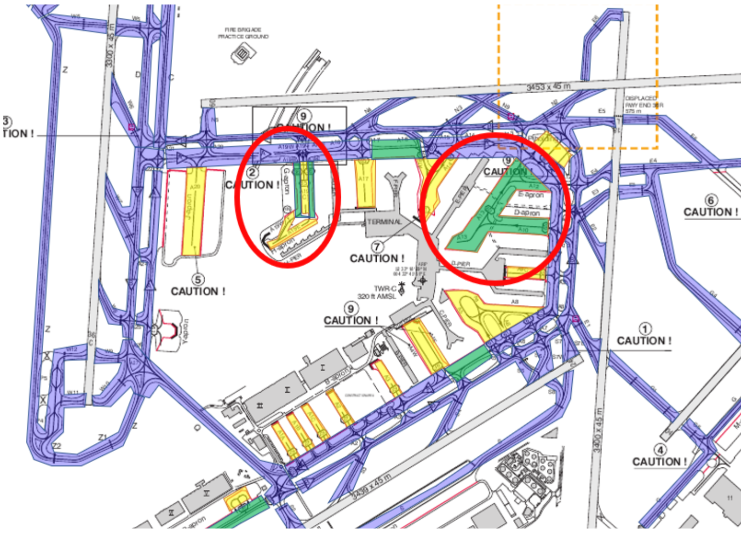

Figure 6.11: Debatable apron taxiways (green, red circled)

The usage of the 'greyness' of the definition of apron taxiways and aircraft stand taxilanes tends to be the result of 'practical drift', as defined by Snook (2000): the system, procedures and regulations are designed in a theoretical environment with implicit assumptions (slower taxiing aircraft at aircraft stand taxilanes), which in practice might differ. Therefore, it is suggested to perform further research on introducing a maximum length of aircraft stand taxilanes, bringing the operational performance back to the baseline performance.

6.6.2 (Bio)mechanics

The (bio)mechanical design principle aims for separating road users with differences in speed, direction, mass and size. As mentioned in Section 5.4, no airport-specific maximum speed is defined; maximum taxiing speeds are airline-specific. Nonetheless, most commercial airlines use 30 *kts* as maximum taxi speed on straight taxiways. Pilots also stated that generally they taxi with lower speeds within the bays[4] - in line with the design criteria for taxilanes. However, they also mentioned that on long taxilanes, speeds are still relatively high.

Placing the above given into perspective of other transportation systems, it can be considered exceptional that there is no maximum speed for given infrastructure on airports. Within road and rail transport, the infrastructure-operator defines maximum speeds for specific parts of infrastructure in order to ensure safe operations. Therefore, it is suggested to explore possibilities of introducing a maximum speed by the airport operator. Additionally, introducing airport-specific maximum

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[4] According to the interviewed pilots, the distinction between taxiways and taxilanes is not not covered within flight academies.

taxi speeds enables defining a difference in maximum taxi speeds between taxiways and taxilanes, increasing the effectiveness of used decreased clearances at taxilanes, since it increases certainty on lower taxi speeds.

Separation in direction at AAS is primarily present on taxiways Alpha and Bravo with defined directions. Yet, ATC regularly deviates from these directions, pilots stated. Besides, currently, at specific moments, taxiway Q is used for both directions alternately at the same time, increasing the chance of traffic standing opposite each other in case of inattention of either ATC or flight crews. A train crash in Amsterdam (with almost 200 injuries and 1 fatality) underpins the importance of mitigating risk of opposite standing aircraft (Dutch Safety Board, 2012). Therefore, as mentioned before, a parallel taxiway South of taxiway Q is currently being planned and constructed, making the full ring-road of taxiways around the central area of AAS double with separated directions (Royal Schiphol Group, 2019a).

Aircraft of different masses and sizes are partly separated in the taxiway system at AAS: the (smaller and lighter) GA-aircraft are handled at Schiphol East, separated from all commercial traffic (generally medium and heavy). Within the central area of AAS were commercial traffic is handled, also a separation of NaBo and WiBo can be seen: On the B-, C-, and H/M- pier, only NaBo aircraft are handled, on the D-pier a mixture of NaBo and WiBo aircraft is handled, where on the E-, F- and G-pier primarily WiBo aircraft are handled. Looking at the black spot analysis in Figure 6.7 with keeping this separation in mind, it can be seen that the largest black spots and black zones are found in the area where NaBo and WiBo merge and mix. Therefore, it is suggested to perform further research on the impact of mixing NaBo and WiBo aircraft in the taxiway system.

6.6.3 Psychologies

In accordance with the psychology design principle, the system shall be "self-explaining". Hence, transferring information to users shall be done through the layout, the environment, traffic signs and regulations. At several intersections in the taxiway system at AAS, information signs (see Figure C.7) are used to indicate directions, as well as markings showing directions (see Figure 6.12).

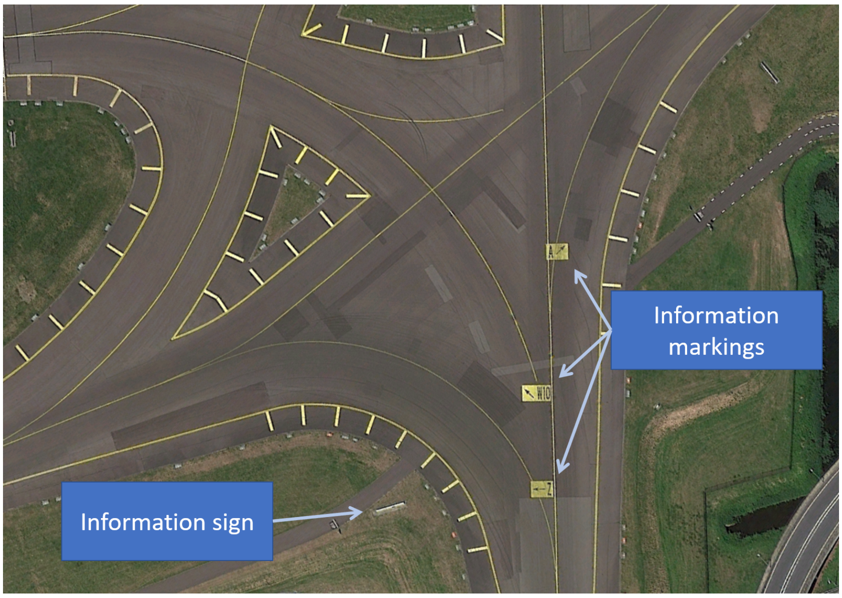

Figure 6.12: Information signs and markings at AAS

However, no visual differences can be seen by pilots on the distinction between apron taxiways and aircraft stand taxilanes: both have aircraft stands along-side, and differences in clearances are too small to be perceived optically. Therefore, in order to increase awareness amongst pilots, it is suggested to investigate distinctions in visual aids for taxiways/apron taxiways and aircraft stand taxilanes; for example different colors of center line markings, dashed center line markings and different colors of center line lights.

Besides, the level of "self-explaining" is questionable within the taxiway system at AAS since during operation regularly defined procedures (e.g. defined directions) are neglected by both flight crews and ATC, as mentioned in Section 6.3 and demonstrated in Section 6.4. It leads to making exceptions on the procedure feel like the standard: ***normalization of deviance***. This terminology was first coined by sociologist Vaughan (1996) in her book in which she investigated the 1986 Challenger space shuttle disaster. She defined it as follows: *"The gradual process through which unacceptable practice or standards become acceptable. As the deviant behavior is repeated without catastrophic results, it becomes the social norm for the organization."* (Vaughan (1996) in Gerstle (2018)). Or as Dekker (2000) describes it: *"Complacency is based on a justified assumption of satisfactory system state, since there is no evidence to the contrary."* Hence, as metaphorized with the Swiss Cheese Model (Reason et al., 2006), insensitivity occurs imperceptibly and sometimes over years because disasters do not happen until other critical factors line up (Price and Williams, 2018). Albright (2017) identified three paths to normalizing deviance: (1) increasingly focus on mission objectives rationalizing away safeguards and common sense, (2) becoming convinced in individual greatness, and (3) individuals becoming so experienced at their profession that complacency displaces competency. Besides, once deviation is ingrained, rooting it out is challenging (Price and Williams, 2018). They concluded that a shift in focus is needed from individual guilt, to the system and related processes. Therefore, it might be worth performing further research on the standards at AAS and reconsider the standards and procedures.

Moreover, as mentioned in Section 6.3, AAS-based pilots got the feeling that for flight crews that visit AAS for the first time (or rarely), taxiing within the taxiway system might be very challenging due to the special procedures and usage of standard taxi routings. The airport's Operations department indicated to receive similar feedback on non-AAS based carriers having more difficulties resulting them in stopping more often and requiring more communication with ATC. On the short term, assigning follow-me vehicles to certain airlines might be a relatively simple solution. On longer terms, further innovations might be required.

6.6.4 Responsibility

In the report by the Dutch Safety Board (2017), several recommendations on the organization of safety management for AAS are provided. Firstly, the board recommended to establish an organisation in which stakeholders cooperate to improve safety. As mentioned in Section 5.6, in order to take an integral approach to the management of safety at AAS, Royal Schiphol Group joined forces with airlines, ATC, ground handlers and refueling services in the Integral Safety Management System (ISMS). Secondly, the board recommended to Dutch Government to take ultimate responsibility for the safety of air traffic at and around AAS through following up nine specific recommendations. It is unknown to what extend the Dutch government already followed up these recommendations. Nonetheless, the Dutch government should take responsibility for the previously discussed extensive number of runway configuration changes at AAS related to noise. The current situation tends to be an over-optimization for a single aspect (noise complaints from local residents). However, a trade-off should be made on the benefits of current noise regulations for local residents on the one hand, and side effects including consequent high number of runway configuration changes implying safety risks on the other hand.

6.6.5 Learning and innovating

This final principle refers to the Deming cycle Deming (1986): starting with the development of effective and preventive system innovations based on knowledge of causes of occurrences (*Plan*). By implementing these innovations (*Do*), by monitoring their effectiveness (*Check*) and by making the necessary adjustments (*Act*), system innovation ultimately results in fewer occurrences.

Through evaluating occurrences, lessons can be learned and new occurrences might be prevented (*plan*). For AAS, the ILT collects all occurrence reports on behalf of the Dutch Government. If necessary, the Dutch Safety Board performs investigations on specific occurrences or incidents. However, room for improvement was found on the occurrence report data: in order to increase and improve opportunities of analyzing the occurrence data report, it would be helpful if all reports would be written in English. Besides, in order to increase accuracy of the in Section 6.4 generated black spot analysis, it would be of large contribution if each report for occurrences within airports would contain a specific location indicator (e.g. intersection name or coordinate).

Next, the taxiway system's safety might be increased through implementation of (new) innovative solutions (*Do*). Two directions of innovations[5] that might be contributing for the safety in taxiways systems on the short to medium term are Airport Collaborative Decision Making (A-CDM) and Advanced Surface Movement Guidance and Control System (ASMGCS).

As mentioned before, the implementation of CDM at AAS improved accuracy of (mostly) outgoing traffic and decreased waiting times of aircraft before line-up (*Checked*). Nonetheless, there is still room for improvements (*Act*): instead of using defined taxi times as input, dynamic taxi times (based on historic data) might be useful. Also specific taxi times per scheduled gate, entry, aircraft type and airline might be contributing to further improve the system.

Through Single European Sky ATM Research (SESAR), the European aviation research program, it was concluded that radio communication for guidance of aircraft during taxiing is near capacity limits on many airports (Straube et al., 2016). Therefore, a surface traffic management concept was developed, which provides individual guidance to taxiing aircraft by automatically and progressively activating taxiway center line lights along the route cleared by the Air Traffic Controller (ATCO): 'Follow the Greens' (SESAR, 2016). In case the cleared route includes a limit and if a physical stop bar is present at this location, the stop bar can also automatically be activated when the aircraft approaches it (SESAR, 2016). Moreover, the automation in this solution developed trough SESAR includes the management of priorities at intersections, based on pre-defined criteria (e.g. aerodrome rules), but with the ability to ATCOs to override the guidance decisions via their working position, which shows activated lights on the radar display (SESAR, 2016). Hence, 'Follow the Greens' shows similarities to 'Green Waves' in road traffic, which has the proven advantage of decreasing emissions (Kelly, 2012). In their research, Straube et al. (2016) validated that 'Follow the Greens' is a safer, quicker and greener surface traffic management concept. At AAS, a project on ASMGCS has started up, Asset Manager 3 mentioned. In this project, 'Follow the Greens' is one of the alternatives. However, to fully implement the technique, quite some time and money is needed. Therefore, also other innovations are considered; for example a moving map in the cockpit to indicate the instructed route. Nonetheless, AAS recently installed 'Follow the Greens' as a proof of concept at the intersection of W5, V, Y and Z. The above mentioned innovations might also contribute to declining the difficulties for foreign carriers currently experiencing difficulties within the taxiway system at AAS.

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[5] There might be (many) more innovations being developed that might contribute to safety in taxiway systems, however, only the innovations items popped up during the performed interviews.

For the long term, the European Commission (2019) defined topics for research in order increase safety and to reduce fuel consumption and emissions in surface operations at airports, which may also be valuable for AAS. For the taxi-in and taxi-out phases, the European Commission (2019) suggests two alternatives:

- *Non-autonomous engine off taxiing used from the gate to the holding point before line up (i.e. for push back and taxi out) and from the runway exit to the gate (i.e. for taxi in to in block). This may be realised with the aircraft using other external means to taxi (e.g. towing trucks, taxibot).*
- *Autonomous engine off taxiing used from the gate to the holding point before line up (i.e. for push back and taxi out) and from the runway exit to the gate (i.e. for taxi in to in block). This may be realised thanks to e.g. electric motors added to the main landing gear and drawing power from either the Auxiliary Power Unit or from an alternative cleaner power source (replacing the APU or being complementary to it) with central control from the cockpit.*

However, these engine off taxiing techniques might impact the taxiway system's infrastructure: In case (electrical) towing trucks are used for the taxiing process, additional infrastructure might be required to enable 'empty' movements (without towing) of the towing trucks. Therefore, Royal Schiphol Group shall keep abreast of the latest developments of this research and anticipate on eventual needed adjustments on AAS's taxiway system.

6.7 RECOMMENDATIONS OF PREVIOUS RESEARCH

As already mentioned in Chapter 1, extensive research on the airside safety of AAS has been performed in the past twice. In the 1990's, Hillestad et al. (1993) (RAND Europe) examined the (external) safety at AAS in a time the airport was about to evolve from airport to mainport. Over two decades later, the Dutch Safety Board (2017) investigated the safety of airside operations at AAS in response to a series of incidents at the airport. Despite Hillestad et al. (1993) and the Dutch Safety Board (2017) concluding that AAS is safe, both also exposed vulnerabilities concerning the safety of airside operations to be tackled before safe growth is possible. Consequently, both provided the following recommendations which are related to the taxiway system:

Recommendations Hillestad et al. (1993):

1. *Safety Management*: The informal nature of aviation safety management and coordination associated with AAS should be replaced by an integrated safety management system.
2. *Maintaining and enforcing high standards*:
   - Due to the economic and political dependence of The Netherlands on the rest of Europe and the World, it is difficult to verify unsafe operations of foreign aircraft and airlines. Nonetheless, it is important that The Netherlands begin examining ways to identify 'risky' carriers;
   - Hazards and incident (occurrence) reporting should not only be possible for Dutch pilots and local ATCOs, but also for foreign flight crews and ground handlers;
   - All organizations associated with AAS should set "safety first". Although it is understood that levels of safety and risk must often be traded off against costs and other benefits, it should also be clear that safety is a first considerations and is not unnecessarily or unconsciously subordinated.

3. *Implementing other safety enhancements*: Technical innovations should be used for improvements on safety.

4. Regularly inform the public and maintain trust in safety management.

Recommendations Dutch Safety Board (2017):

1. *Develop a future proof operational concept:*
    - Reduce the daily number of runway configuration changes;
    - Reduce the complexity of airside infrastructure.

2. *Reduce current and future safety risks by:*
    - Monitor and evaluate deviations of procedures and standards by ATCOs;
    - Assess the risks of stacking of safety risks and related mitigating measures.

3. Investigate the effect of an increase in number of movements on the safety on forehand and by an integral approach and take measures to structurally control these effects.

4. Develop a common vision for the safety of AAS.

5. Develop an integral safety management system.

6. The Dutch Government should take the end responsibility for the safety of air traffic at and around AAS and regularly report on the safety of the airport.

From the two lists of recommendations it can be seen that a number of recommendations of Hillestad et al. (1993) are also recommended by Dutch Safety Board (2017), suggesting that they were not yet (fully) followed up by 2017. On the management of safety, both recommended to develop an integral safety management system with a common vision for safety. Nowadays, these recommendations are followed up by the initiation of the ISMS. Both also recommended the Dutch Government to regularly update the public on the safety of the airport and take the ultimate responsibility. The Dutch Minister of Infrastructure and Water Management (2019b) currently twice per years informs the parliament on the safety of AAS. However, as mentioned in Section 6.6, it is unknown to what extend the Dutch government has taken the ultimate responsibility. Despite, the Minister set the criterion that an increase in number of movements will only be allowed if this is demonstrable safely possible. The recommendation of Hillestad et al. (1993) to broaden the ability of occurrence reporting has been followed up by the occurrence reporting regulations of the European Union (2014). Besides, technical innovations are investigated to be used for improvements on safety (e.g. 'Follow the Greens'). For the other recommendations it is unknown to what extend they are already followed up.

6.8 CONCLUSION

This chapter analyzed the taxiway system of AAS on the KPI *safety* through performing several analysis, thereby answering Sub Question (SQ) 9. The gained insights on the safety of the taxiway system at AAS provides inputs for answering the Research Question in Chapter 7 and for recommendations on making steps towards improving airport taxiway systems.

In the period between 1 January 2009 and 31 September 2019, AAS handled 4,387,261 movements. In this period of time, 1,766 relevant occurrences related to the taxiway system were reported. As mentioned in Section 4.2, the weight factors of the safety measurement (Equation 4.1) are not yet determined due to time limitations.

Therefore, in this research for all occurrence categories, the weight factor f_c will be set to 1.0, resulting in the following measurement of safety:

> *Average **Safety** over the past decade = 3.7 occurrences per 10,000 movements*

Over the past decade, the number of occurrences per 10,000 movements showed an increasing trend and increased by 505%. However, the used occurrence report data does not permit any definite conclusions to be dawn on number of occurrences, since legislation on reporting and reporting behaviour has changed over the years. Nonetheless, the extensive increase in occurrence reports suggests an actual increase in number of occurrences. The black spot analysis demonstrated that a majority of the reported occurrences are located around the central area of AAS, along taxiways Alpha and Bravo. The biggest black zones were found in the area close to the threshold of runway 24, which also was identified as one of the busiest areas in the heat map. Besides, a high number of occurrences are reported in the North-East area of taxiways Alpha and Bravo.

Moreover, for the first time a taxiway system was analyzed through the sustainable safety framework as developed for road traffic. Assessing the taxiway system of AAS on the principles of sustainable safety denoted several issues. For example, the design principles exposed ambiguity within the taxiway system: the unclear definition of apron taxiways ('grey roads') seems to be utilized for the sake of handling peaks in traffic demand, undervaluing the impact on safety.

In the end, a number of challenges and opportunities are found for both AAS-specific and safety within taxiway systems in general. Below, an overview of the challenges and opportunities is provided. Next to the below listed challenges and opportunities, several topics for further research are found, which will be elaborated in Chapter 7.

General challenges and opportunities

1. Opportunities in improving safety by modifying Standards and Recommended Practices (SARPs);
2. Opportunities for improving taxiway system's safety assessment techniques.

Challenges and opportunities for Amsterdam Airport Schiphol

1. Supportive tools for decision making;
2. Better understanding of occurrence reports;
3. Usage of the greyness of the taxilane definition;
4. Difficulties for rare visitors;
5. Number of runway configuration changes;
6. Difficult area around threshold of runway 24;
7. Dealing with the current procedures;
8. Using innovations for improvements;
9. Limitations of the current system.

7 CONCLUSIONS AND RECOMMENDATIONS

The almost ceaselessly growing Air Transportation System (ATS) has lead to concerns across airport on how to deal with this growth. Also Amsterdam Airport Schiphol (AAS) experienced large increases in number of passengers and movements over the last decades: the current limit of 500,000 annual movements of the airport is (nearly) reached. Before stretching the current limit, AAS shall demonstrate that it growth is safely possible (Dutch Minister of Infrastructure and Water Management, 2019a). In the past, both Hillestad et al. (1993) and the Dutch Safety Board (2017) investigated the safety at AAS and concluded that, despite vulnerabilities, the airport was safe.

The objective of this research is to explore challenges and opportunities towards improving airport taxiway systems. Therefore, first, a currently lacking definition for taxiway system at systems level is defined. Besides, Key Performance Indicators (KPIs) for taxiway systems are defined in order to identify parameters for improving the system based on stakeholders' point of views. Also methods for assessing taxiway systems on these identified KPIs are defined. Next, AAS is used as a case study to analyze the performance of the taxiway system at the airport on the defined safety KPI. Based on this analysis, challenges and opportunities within the taxiway system are identified. In this chapter, the conclusions of this research are provided, as well as recommendations for making steps towards improving airport taxiway systems, thereby answering the Research Question: *What are challenges and opportunities towards improving airport taxiway systems?*

This chapter is structured following the V-model of the ATS by Schmitt and Gollnick (2016). Hence, first general conclusions from the analysis at system's level - including a definition of taxiway systems, KPIs and proposed assessment methods - are provided in Section 7.1. Second, a comprehensive conclusion of findings on the safety analysis of the taxiway system at AAS is provided in Section 7.2. Afterwards, on the integration path of the v-model, recommendations for the taxiway system at AAS specifically are provided for the found challenges and opportunities (Section 7.3). Next, non-airport specific (general) recommendations are listed per found challenge/ opportunity (Section 7.4). Next to an explanation, each recommendation includes an indication of the related interaction field of the SHELL model. Moreover, it is indicated for each recommendation in which step of the Deming cycle the recommendation fits as well as in which implementation stage as defined by SWOV (2018). It should be noted that the listed general recommendations are applicable for AAS too. In the end, recommendations for further research are provided in Section 7.5.

7.1 GENERAL CONCLUSIONS

First of all, a definition for taxiway systems is provided:

The taxiway system is that part of the aerodrome surface movement area intended for safely connecting runways with aprons and facilitating all other movements of aircraft other than takeoff or landing under guidance of Air Traffic Control (ATC).

In order to make the definition more specific, it is split up in an operational definition and a physical definition:

The taxiway system is operationally used under guidance of ATC:

- *for arriving aircraft from the moment the cockpit of the aircraft intercepts the center line marking of the taxiway used for exiting the runway, maneuvering over the airport surface on its own power, until the aircraft crosses the ATC service boundary;*
- *for departing aircraft from the moment the aircraft starts maneuvering over the airport surface on its own power, until takeoff power is applied on the runway; or*
- *when aircraft are being towed in a forward direction by a towing truck.*

The physical taxiway system exists of those surfaces of an airport within the ATC service boundary, excluding the runway, and being either a taxiway, apron taxiway, aircraft stand taxilane, holding bay, Rapid Exit Taxiway (RET), runway turn pad or overlap of the entry/exit from/to the runway, including the related sub-components, being visual aids, drainage infrastructure and the (pavement) construction.

Key Performance Indicators

Secondly, based on literature and interviews amongst taxiway systems' stakeholders, 13 indicators for assessing taxiway systems were identified, including four KPIs: safety, capacity, robustness and environmental impact. For each, a measuring method is defined, as well as an assessment method. The KPIs are described in Section 4.3. However, the major findings are discussed below.

To quantify safety, Baltazar et al. (2018) measure the number of accidents and serious incidents. Since on taxiway systems speeds are relatively low, the impact of occurrences is lower. Therefore, not only accidents and serious incidents should be of interest, but also incidents of lower severity categories should be taken into account. However, data on occurrences of lower severity categories is dependent on reporting data, thereby making measurement sensitive for subjective reporting. A methodology of analyzing Potentially Hazardous Interactions (PHIs) based on processing surveillance radar data as proposed by Ford et al. (2014) might be useful to validate occurrence report data and supplement the data with unreported occurrences. Additionally, since not all types of occurrence have similar impact on safety, six described occurrence categories are entailed in the safety measure with specific weight factors. Moreover, the gauge (Equation 4.1) is normalized to *per movement* to enable comparisons amongst airports.

For assessing the *safety* KPI, a for taxiway systems new vision on safety was introduced: sustainable safety. The aim of sustainable safety is achieving safety by systematically reducing underlying risks of the traffic system through technical and organizational principles, with a focus on human factors (SWOV, 2018). This is in line with the by ICAO (2018b) defined approaches to safety within the aviation industry. It has been recognized that rather than adapting people to a system, the system should be adapted to people's abilities and desires, which is also known as 'safety by design'. Besides, the term 'complexity' is often referred to in relation to safety within taxiway systems. However, quantifying complexity showed to be challenging. Therefore, using the term 'complex' in relation to taxiway systems requires carefulness: before identifying the system as complex, it should be considered in which perspective it is regarded and the legacy of the airport should be taken into account as well. Moreover, in case the terminology of complexity is used, it can be split up in two components: infrastructural and operational complexity.

Also the *capacity* KPI turned out to be hard to quantify, requiring additional research to define a gauge. Based on the interviews and by Mota and Boosten (2014) identified factors, the following multi function for capacity was defined:

$$\text{Taxiway system capacity} = f(\textit{business model, infrastructure, societal conditions}).$$

Quantifying the capacity of taxiway systems should be given high priority, since it supports decision making and provides by figures substantiated insights on the saturation of the system.

In the master planning of taxiway systems, the *robustness* KPI plays an important role. Yet, larger airports are struggling in making the trade-off between flexibility and simplicity. Finally, it should acknowledged that the *environmental impact* KPI can not be neglected. Recently, Remkes et al. (2020) underpinned that airports should put effort in declining environmental impact, also within taxiway systems.

Safety analysis

Next, the taxiway systems of AAS was analyzed on the KPI *safety*. Below, non-AAS specific findings from the safety analysis are discussed.

In general, it can be concluded that many aspects within the airport system are related to each other, making pointing at specific issues to solve rather difficult. The same holds within taxiway systems. When analyzing a taxiway system, it is important to look outside the boundaries of the taxiway system: The usage of the taxiway system largely depends on the usage of runways and aprons. Hence, the layout and configuration of the analyzed airports are of large importance and the history and legacy of the airport should be understood and appreciated. Moreover, the airport's operational concept, including the operational concept of home carriers, impacts the usage of the taxiway system. Consequently, comparing taxiway systems of airports should not be done without truly considering above described aspects.

Taxiway systems are designed and developed following the in Annex 14 by ICAO (2018a) defined Standards and Recommended Practices (SARPs). For European airports, the on International Civil Aviation Organization (ICAO)'s Annex 14 based Certification Specifications and Guidance Material for Aerodromes Design of EASA (2017) are used. Within Annex 14, safety can be seen as the thread. Nonetheless, it was found that the definition and distinction of apron taxiways and aircraft stand taxilanes is debatable: the only difference in definition is that aircraft stand taxi lanes only provide access to aircraft stands, whereas apron taxiways (next to providing access to aircraft stands) also provide through taxi-routes. Since no definite definition of through taxi-routes is provided, airports might make usage of the 'greyness' of the definition for the sake of handling increasing traffic demand, undervaluing the impact on safety, by easier defining a taxiway as aircraft stand taxilane (requiring less horizontal spacing). Hence, the usage of the 'greyness' of the definition tends to be the result of 'practical drift', as defined by Snook (2000): the system, procedures and regulations are designed in a theoretical environment with implicit assumptions (slower taxiing aircraft at aircraft stand taxilanes), which might differ in practice. Moreover, no visual differences can be seen by pilots on the distinction between apron taxiways and aircraft stand taxilanes: both have aircraft stands along-side, and differences in clearances are too small to be perceived optically. Compared to other transportation system, one operational procedure in the taxiway system can be considered exceptional: no airport-specific maximum taxi speed is defined. Contrary, maximum taxiing speeds are airline-specific. Nonetheless, most commercial airlines use 30 *kts* as maximum taxi speed on straight taxiways. Pilots also stated that generally they taxi with lower speeds near gates (on taxilanes). However, they also mentioned that on long taxilanes, speeds are still relatively high.

In the end, analyzing occurrence report data (as collected by the European Union (2014)) is found to provide broad opportunities. Yet, the current reporting system causes limitations. Firstly, free-text in the occurrence report data for AAS appeared to be in both English and Dutch, making (automatic) analyses through word processors difficult. Secondly, occurrence categories are conform the by ICAO defined categories of accident and incidents, of which incidents are divided into five severity sub-categories. However, since 'incident' is one of the possible options within the occurrence category, only a limited number of occurrences are defined as one of the five incident categories. For the case of AAS, 1,281 of the 1,766 reported occurrences were classified as 'incident', without specific incident category. Thirdly, analyzing the occurrence report data for black spots in a taxiway system unveiled difficulties, since the location field within the occurrence report data only contains data up-to the level of the aerodrome. For the case of AAS, 846 of the 1,766 reported occurrences did not contain a specific location within the taxiway system. In other words, for reporting occurrences within taxiway systems, currently no specific location within the concerned aerodrome is required. Only within the free-text, reporters might refer to a location.

7.2 CONCLUSIONS FOR AMSTERDAM AIRPORT SCHIPHOL

As mentioned, the taxiway system of AAS was used as a case study. Hence, several analyses on the safety of AAS's taxiway system were performed. Below, the conclusions and findings of these analyses are discussed.

Historical perspective

The configuration of AAS can be seen as a legacy of Jan Dellaert: his around 1950 developed master plan for AAS formed the basis for the airport as it is known nowadays. Dellaert's plan, with a tangential runway system and a central traffic area, enabled the airport to operate at maximum capacity regardless of the wind direction. The by Schiphol and Royal Dutch Airlines (KLM) further elaborated plan was based on 100,000 annual movements and 2 million passengers around the 1970s/1980s (Schiphol, 1953). As AAS was proposed to become a center in the European and Intercontinental air traffic, the aim was to have the airport meet the highest requirements (NACO, 1953). In general, safety was the most important criterion for assessing the design, followed by capacity. For the airside infrastructure, next to the general criteria, important criteria were taxi distances between the runways and terminal areas, and nuisance for neighbours. Nonetheless, NACO (1953) recognized that amongst the objectives of the design, contradictions were present Consequently, they concluded that the most satisfying design would be a compromise at all times. Besides, Netherlands Airports Consultants (NACO) concluded that, despite the fact that the proposed tangential system might suggest a high capacity due to the large number of runways, the capacity is restricted to specific meteorological conditions (Van Wageningen, 1953).

The extraordinary increase in traffic demand and operational concept of KLM (causing peaks in traffic demand over the day) exposed the system's vulnerabilities. In the current state, the system seems to have reached its operational limits. The 'ring road' of taxiways (Alpha and Bravo), parallel to the runways around the central traffic area, creates a boundary for expansion of piers, as was already expected during the development of the master plan (Van Wageningen, 1953). As a result, piers and adjacent aircraft stands are currently located very close to - and even along - through taxi routes on taxiways Alpha and Bravo, which users experience as undesirable and which is not in line with the design principles of sustainable safety. Besides, during taxi-in after landing, aircraft regularly have to hold due to unavailability of gates and stands.

Despite the tangential runway system at AAS, the number of runway configuration changes at the airport is extremely high in an international context. Due to the tangential system, most changes are not weather based. Instead, 90% of the on average 18 daily configuration changes are related to noise regulations, resulting in a contradiction: the Dutch government requires AAS to follow up recommendations of the Dutch Safety Board (2017) to reduce the daily number of runway configuration changes on the one hand, where on the other hand the Dutch government set the regulations on noise restrictions causing the high number of changes. The current situation tends to be an over-optimization for a single aspect (noise complaints from local residents). Moreover, where the Dutch Safety Board (2017) focuses on safety implications of this large number of daily configuration changes for the runway system, it should be recognized that runway configuration changes also impact the taxiway system: each runway configuration results in a certain traffic flow of taxiing aircraft. Since there are a lot of runway configurations possible at AAS due to the large number of runways, there are also a lot of traffic flows possible in the taxiway system - there is a large number of Origin-Destination pairs between gates and runways, with additional dependency of usage of other runways. The changes in traffic flows within the taxiway system might also lead to conflicting flows. Besides, the large number of configuration changes decreases the predictability for flight crews on taxi routings. A situation with changing taxi routes especially causes risks for flight crews that visit AAS rarely - who already seem to experience challenges in the taxi process under normal conditions. Consequently, the side effects of the noise-related regulations should be considered in a broader perspective, including safety risks within the taxiway system of AAS.

Complexity and occurrence report data

One of the other concerns of the Dutch Safety Board (2017) is the complexity of the taxiway system at AAS. Conversely, most interviewed stakeholders do not necessarily experience it as such. For flight crews that are used to the system (including the used standard taxi routes and the large number of possible routes) the taxiway system at AAS is rather simple, pilots stated. Nonetheless, the interviewed pilots can imagine that for flight crews that visit AAS for the first time (or rarely), it might be very challenging.

Possibly, the large share of occurrences of the category indicating that *flight crews* deviate from ATC instructions or standard procedures (on average > 50%) contributes to the substantiation of the taxiway system being (possibly) (operational) complex. The large number of deviations from standard procedures is generally noticeable and also recognized amongst pilots and airport representatives. It is also acknowledged that this might cause safety risks. Often deviating from procedures and standards in the operation inclines users to make the deviation a habit: *normalization of deviance* (Vaughan, 1996). By repeatedly deviating from procedures and standards without hazards, taking the risk of deviating is accepted. However, rooting out deviation is challenging: a shift in focus is needed from individual guilt, to the system and related processes.

Another possible contributor to (possibly) (infrastructural) complexity of the taxiway system is the extensive quantity of infrastructure. The airport is lacking a vision for the taxiway system: should it aim for simplification or for flexibility? No unambiguously answer can be provided to this question. Setting up such a vision would help decision making for designing new/adjusted infrastructure, since it reduces room for discussion. Besides, the airport recently initiated a project on developing a strategy for taxiway maintenance.

Analyzing the occurrence report data revealed an increasing trend in occurrence reports over the past decade: the number of occurrence reports per 10,000 movements increased by 505%, and showed an average of 3.7 occurrences per 10,000 movements over the past decade. As mentioned, the majority of reports regards deviations from instructions of ATC or from standard procedures by *flight crews*. Thereafter, the major contributing occurrence category (on average 27%) regards occurrences of aircraft with *other vehicles* such as towing movements or service vehicles. Besides, a large increase of number of occurrence reports on *taxi speed* exceeding is seen, which might be (partly) caused by increasingly monitoring taxi speeds by airlines. The large share of occurrences related to deviations by *flight crews* seems a superficial observation: flight crews are referred to for the majority of guilt. Yet, as stated by Price and Williams (2018), to improve the system, a shift in focus is needed from individual guilt, to the system and related processes. Nonetheless, the occurrence report data does not permit any definite conclusions to be drawn on numbers of occurrences, since legislation on reporting and reporting behaviour has changed over the years.

Black spot analysis

From the black spot analysis as shown in Figure 6.7, it was concluded that (within the research scope) most occurrences are reported along taxiway Alpha. The largest black zone was found close to the threshold of runway 24, which also was identified as one of the busiest areas within the system. In this area, many conflicting traffic flows may occur: (1) traffic departing from runway 24, taxiing from all directions towards one of the entries, (2) traffic departing from the A-apron, B- or C-pier taxiing towards the North over taxiway Bravo (along entries of runway 24), and (3) arriving traffic for the C/D-bay from all directions. Also interviewees pointed at this area as most difficult area in the taxiway system of AAS. Next to the many conflicting traffic flows caused by its location within the system, interviewees add another issue within this area: the borders of both ATC's 'Ground'-control areas and Schiphol's 'Apron'-control are located within this area: the border is located East-West at the Southern pier of the D-pier (around A9). Pilots understand that it is well for ATC, but increases workload for pilots. Thus, pilots experience the current situation as undesirable.

Additionally, a high number of occurrences are reported in the North-East area of taxiways Alpha and Bravo. In this 'corner' of AAS's central area, a lot of runway exits/entries of two different runways are situated close to each other. Besides, the major remote holding apron is located in the middle of the area, as well as the D/E- (NaBo and WiBo) and E/F-bays (WiBo). When looking at Table 6.3, it can be seen that primarily taxiways A13 and N2 (which crosses runway 09/27) contribute to the high number of occurrences in this black zone.

Another area showing difficulties is the intersection at the Western end-node of taxiway Quebec, close to the threshold of runway 36C. The conflicting traffic flows and high traffic demand results in dangerous situations. Moreover, two of three by the Dutch Safety Board investigated incidents (2011, 2019a) underpin the safety issues in this area and suggest that also the high number of links at the intersection contribute to the complexity of this intersection.

For the largest identified black zones, word clouds are created. The following words stand out: *give way, runway, instead* and *vacating*. These words suggest that major occurrences are related to giving way to each other and vacating runways, probably associated to the described separation procedures at AAS. Moreover, ATC might request flight crews to exceed taxi speed limits in order to expedite their runway-vacating because of successively aircraft on short final. Hence, these findings imply to underpin the increasing pressure from ATC on flight crews and deviations by flight crews from procedures.

Sustainable Safety

Furthermore, a new safety assessment method was applied for the case of AAS: assessing the taxiway system on the principles of the sustainable safety vision, which is based on the awareness of importance of human factors in achieving safe transport. Primarily, the taxiway system at AAS follows a clear hierarchy and structure. Nonetheless, several 'grey roads' (apron taxiways) are found. This might cause drawbacks around the C- and F-pier in particular, where aircraft stands are located along taxiway Alpha. Two examples of taxiways designed as aircraft stand taxilane showed ambiguity within the system. These imply that for the sake of handling peaks in traffic demand, the 'greyness' of the definition is being utilized, undervaluing the impact on safety.

Within the central area of AAS, were commercial traffic is handled, a separation of Narrow Body aircraft (NaBo) and Wide Body aircraft (WiBo) can be seen: On the B-, C-, and H/M- pier, only NaBo aircraft are handled, on the D-pier a mixture of NaBo and WiBo aircraft is handled, where on the E-, F- and G-pier primarily WiBo aircraft are handled. Looking at the black spot analysis in Figure 6.7 with keeping this separation in mind, it can be seen that the largest black spots and black zones are found in the area where NaBo and WiBo merge and mix.

The level of "self-explaining" is found to be questionable within the taxiway system at AAS, since during operation, as mentioned before, standard procedures are regularly deviated from. Besides, AAS-based pilots got the feeling that for flight crews that visit AAS for the first time (or rarely), taxiing within the taxi system might be very challenging due to the special procedures and usage of standard taxi routings. Eventually, the taxiway system at AAS shows room for improvement on both the functional and psychological design principle of sustainable safety, where the (bio)mechanical design principle is fairly met.

In the last years, AAS has improved on the organizational principles of sustainable safety. Royal Schiphol Group joined forces with airlines, ATC, ground handlers and refueling services to take an integral approach to the management of safety at AAS by founding the Integral Safety Management System (ISMS). Besides, the airport works on implementing innovations within the taxiway system. The implementation of Collaborative Decision Making (CDM) improved accuracy of (primarily) outgoing traffic and decreased waiting times of aircraft before line-up. Nonetheless, there is still room for improvements: instead of using defined taxi times as input, dynamic taxi times (based on historic data) might be useful. Also specific taxi times per scheduled gate, entry, aircraft type and airline might be contributing to further improve the system. Moreover, the airport started up a project on Advanced Surface Movement Guidance and Control System (ASMGCS). In this project, 'Follow the Greens' is installed as a proof of concept at the intersection of W5, V, Y and Z. However, full implementation of 'Follow the greens', is cost and time expensive. Therefore, within the ASMGCS-project, the airport also considers other innovations like a moving map in the cockpit to indicate the instructed route.

Final conclusions

Concluding, the present taxiway system at AAS seems to be safe, yet shows challenges and opportunities for improvements. Looking at the legacy of AAS, Jan Dellaert had an excellent foresight when proposing his master plan back in 1953. One of his starting points was the importance of transfer passengers, which nowadays represent 36.6% of the total number of passengers at AAS. Dellaert's plan also showed to deliver a solid airport system: the design based on 2 million passengers and 100,000 movements in the 1970s/1980s appeared to be able to handle 71.7 million passengers and almost 500,000 movements last year with extended terminal areas and piers in the by Dellaert designated central traffic area, and one additional runway. Nonetheless, the present taxiway system tends to reach its safe operational limits, suggesting the system reached the 'wear-out' phase of the bathtub curve (Klutke et al., 2003). This might partly be caused by the 'practical drift' throughout the years. The pressure from ATC on flight crews seems to increase and deviations from standards and procedures are ingrained of which investigations on past incidents in both aviation and rail underpinned the consequent safety risks. Moreover, the 'greyness' of definitions is utilized by the airport in order to handle the peak traffic demands within the set systems boundaries. Despite the steps the aviation industry in The Netherlands has made towards an integral approach on safety, care must be taken to ensure that the taxiway system is not underexposed and that safety continuously remains a first considerations and is not unnecessarily or unconsciously subordinated.

Although the taxiway system of AAS was only analyzed on the safety KPI, links with the other KPIs are found: As mentioned, the present system appears to reach its limits. However, no quantified *capacity* has been determined yet. Within the referred to lacking vision on the trade-off between simplification or maximizing flexibility of the taxiway system, a link can be found with the *robustness* KPI, which can be seen as a factor in the trade-off. In the end, the by the airport initiated innovative projects in relation to the taxiway system like 'Follow the Greens' (ASMGCS) and CDM have proven to be able to decrease the *environmental impact*, making them two-fold of added value.

With regard to the criteria the Dutch Minister of Infrastructure and Water Management (2019a) set for AAS to grow, the following can be concluded for the contribution of the taxiway system: As a result of innovations (e.g. CDM and ASMGCS), the taxiway system might have a positive effect on the *environment* criterion. The (noise) nuisance of the taxiway system is very limited. Nonetheless, the current number of runway configuration changes as a result of nuisance create safety risks within the taxiway system, for which a recommendation will be provided in the next section. The quality criterion is not applicable for the taxiway system. In the end, by following up the in the next section provided recommendations, the safety within the taxiway system at AAS is expected to be sufficient to facilitate growth.

7.3 RECOMMENDATIONS FOR AMSTERDAM AIRPORT SCHIPHOL

This section provides recommendations based on the identified challenges and opportunities for the taxiway system of AAS. Next to an explanation, each recommendation includes an indication of the related interaction field of the SHELL model. Moreover, it is indicated for each recommendation in which step of the Deming cycle the recommendation fits as well as (if applicable) in which implementation stage as defined by SWOV (2018).

1. Supportive tools for decision making.

Recommendation 1: The present taxiway system appears to reach its safe operational limits. Yet, no quantified capacity has been determined yet to support this observation. Hence, it is recommended to determine the saturation rate (and thus the capacity) of the airport's taxiway system in order to support decision making in the future. However, quantifying capacity of taxiway systems requires further research.

SHELL interaction(s):	Software/Environment
Deming step:	Check
Implementation stage:	N/A

Recommendation 2: Additionally, in order to support decision making in designing new/adjusted infrastructure and reducing room for discussion, it is recommended to define a vision for the taxiway system. In this vision, based on sustainable safety, a trade-off should be made between simplicity and flexibility of using the taxiway system. Preferably, the vision is set up by the airport operator, in cooperation with Air Traffic Control the Netherlands (LVNL) (in the role of service provider).

SHELL interaction(s):	Software/Liveware
Deming step:	Plan
Implementation stage:	N/A

Recommendation 3: To support defining a vision, first, it is recommended to analyze the taxiway system of AAS on the other in Section 4.3 defined KPIs. In further analyses on the taxiway system of AAS, it is recommended to involve General Aviation (GA)-aviation too, in order to get comprehensive insights. Moreover, it is recommended to validate the in this research developed heat map on historical ground movement data.
SHELL interaction(s): Software
Deming step: Plan
Implementation stage: N/A

Recommendation 4: In case historical ground movement data is available, a similar investigation as performed by e.g. Ford et al. (2014) is recommended. In such investigation, PHIs in the past can be identified and combined with occurrence report data to gain further insights on specific taxiway system factors that contribute to decreased safety.
SHELL interaction(s): Software
Deming step: Check
Implementation stage: N/A

2. *Better understanding of occurrence reports.*

Recommendation 1: Since the occurrence report data does not permit any definite conclusions to be drawn due to changed legislation and reporting behaviour over the years, it is recommended to investigate the development of actual number of occurrences over the past decade. Next to PHIs, the ILT might play an important role as occurrence report data collector for gaining these insights.
SHELL interaction(s): Software/Liveware
Deming step: Plan
Implementation stage: N/A

Recommendation 2: The occurrence report data showed that 27% of occurrences within the taxiway system at AAS concerns occurrences of aircraft with other vehicles (e.g. tow movements or service vehicles). It is recommended to investigate potential causes of these occurrences, since only little is known on this topic.
SHELL interaction(s): Software/Liveware
Deming step: Plan
Implementation stage: Mitigation

3. *Usage of the greyness of the taxilane definition.*

Recommendation: Based on the functional design principle of sustainable safety, a discussion/debate is opted on the definition of taxilanes at A13, A19E and A19W AAS. Taxiways A19E and A19W are primarily used by NaBo aircraft to and from the H/M-pier, where taxiway A19C is used by WiBo aircraft for access to G-stands. Hence, along the G-pier, taxiways A19E and A19W provide a through-route to the H/M-pier and taxi speeds might be expected to be relatively high for taxilanes (as which they are currently designed). Therefore, in order to increase safety in this bay, it is recommended to consider re-defining taxiways A19E and A19W as apron taxiways with corresponding design criteria.
SHELL interaction(s): Environment
Deming step: Act
Implementation stage: Minimization

4. *Difficulties for rare visitors.*

Recommendation: Despite the by Hillestad et al. (1993) acknowledged difficulties in international perspective, it is recommended to investigate differences amongst (reported) occurrences of regular and irregular AAS visitors and investigate how to ensure safe operations for both. On the short term, assigning 'Follow me'-vehicles to rare visitors might provide opportunities.
SHELL interaction(s): Software/Liveware
Deming step: Plan
Implementation stage: Minimization

5. *Number of runway configuration changes.*

Recommendation: The Dutch government should take responsibility for the discussed extensive number of runway configuration changes at AAS related to noise. The current situation tends to be an over-optimization for a single aspect (noise complaints from local residents). Therefore, a trade-off is recommended on the benefits of current noise regulations for local residents on the one hand, and side effects including consequent high number of runway configuration changes implying safety risks on the other hand. In this trade-off it should be acknowledged that runway configuration changes not only impact the safety around runways, but also within the taxiway system due to changes in traffic flows.
SHELL interaction(s): Environment/Liveware
Deming step: Act
Implementation stage: Minimization

6. *Difficult area around threshold of runway 24.*

Recommendation 1: Currently, the area close to the threshold of runway 24 is not defined as hot spot (Section 3.3). Yet, both interviewees and the black spot analysis showed difficulties in this area. Consequently, it is recommended to re-consider this area as hot spot, in order to increase awareness amongst users.
SHELL interaction(s): Software/Environment
Deming step: Act
Implementation stage: Mitigation/Minimization

Recommendation 2: One of the borders of both 'Ground'- and 'Apron'-control are located in one of the most difficult areas at AAS: around the threshold of runway 24. Moreover, the fact that both 'Ground'- and 'Apron'-control operate in the same area is considered as undesirable: a lot of mutual coordination is required. In the end, since interviewed stakeholders experience the bays around piers at AAS as very crowed, a re-organization of the ATC-system for movements on the surface of AAS is proposed: upgrade 'Apron'-control to become part of LVNL and let them guide and control all traffic within the bays (if needed split up in two or more areas). This enables 'Ground'-control to focus on all traffic (including towed-traffic) on through-routes within the taxiway system. In this was, 'Ground'-controllers can support flight crews more intensively on intersections and reduce the occurrences of lacking ATC instructions. Besides, this situation would provide a more clear structure of communication areas and the border around the threshold of runway 24 might become unnecessary. Pilot 1 supports this suggestion and sees positive opportunities. Pilot 2 is more careful: he mentions that at Miami International Airport a similar system is used, however, the flight crew there has to be in contact with both 'Gate'-control (proposed 'Apron'-control at AAS) and 'Ground'-control simultaneously. If this contact would not be required simultaneously, also Pilot 2 sees advantages of the re-organized system. In Chapter 8, an additional advantage of this situation (outside the scope of this research) is discussed.

SHELL interaction(s): Liveware
Deming step: Act
Implementation stage: Minimization/Elimination

7. Dealing with the current procedures.

Recommendation 1: Created word clouds imply that major occurrences within the largest black zones are related to giving way to each other by flight crews and vacating runways. Moreover, ATC might request flight crews to expedite vacating the runway for successively aircraft on short final. It is therefore recommended to investigate the degree of following-up of the separation procedures on AAS by flight crews and the required level of interference and guidance by ATC.

SHELL interaction(s): Software
Deming step: Check
Implementation stage: Minimization

Recommendation 2: *'Normalization of deviance'* seems to be present within the taxiway system of AAS. Once deviation is ingrained, rooting it out is challenging. It a shift in focus is needed from individual guilt, to the system and related processes. Therefore, it is recommended to further investigate advantages of defining used alternatives as new standards or to abolish certain procedures in order to increase alertness.

SHELL interaction(s): Software
Deming step: Check
Implementation stage: Minimization/Elimination

8. Using innovations for improvements.

Recommendation 1: It is recommended to continue working on safety increasing ASMGCS projects like 'Follow the Greens', since they are very promising and also have a positive effect on environmental impact.

SHELL interaction(s): Hardware
Deming step: Check
Implementation stage: Minimization/Elimination

Recommendation 2: The introduction of Airport Collaborative Decision Making (A-CDM) showed to be very promising for the taxiway system by enabling better planning of traffic flows within the system. Nonetheless, room for improvement is found: by making use of dynamic taxi times (e.g. based on historical data), even more accurate taxi times can be estimated and thus more accurate milestones can be determined.

SHELL interaction(s): Hardware
Deming step: Act
Implementation stage: N/A

Recommendation 3: The European Commission (2019) defined topics for research in order to reduce fuel consumption and emissions and increase safety in surface operations at airports, which may also be valuable for AAS. Examples of innovations are aircraft using other external means to taxi (e.g. towing trucks, taxibot) or electric motors added to the main landing gear and drawing power from either the Auxiliary Power Unit or from an alternative cleaner power source (replacing the APU or being complementary to it) with central control from the cockpit. Royal Schiphol Group is recommended to keep abreast of the latest developments of such

research and anticipate on eventual required adjustments on AAS's taxiway system on the long term to remain future-proof.
SHELL interaction(s): Environment/Hardware
Deming step: Plan
Implementation stage: Minimization/Elimination

9. Limitations of the current system.

Recommendation: The performed analysis of the taxiway system of AAS through the sustainable safety framework showed room for improvements which can not be solved in the short and medium term, but might be possible on the long term. Especially the location of gates relative to the location of through taxi-routes worries. Besides, the number of gates and stands appears to be insufficient, resulting in arriving aircraft being required to hold (even on taxiways) until a stand becomes available. Moreover, as mentioned, the current tangential runway system seems to have reached its limits. Therefore, a re-design of the airport based on sustainable safety, taking the identified KPIs for the taxiway system into consideration is recommended.
SHELL interaction(s): Environment
Deming step: Plan
Implementation stage: Elimination

7.4 GENERAL RECOMMENDATIONS

Next to the recommendations for AAS specifically, recommendations to make steps towards improving taxiway systems at airports in general are provided on two in Section 6.8 identified opportunities. Besides, in advance one general overall recommendation is made: Within (re)design of airports, the taxiway system should not be an afterthought. A more integral approach is required, taking the in this research identified KPIs for taxiway systems into account. Also within safety management of airports, the safety in taxiway systems should be part of an integral approach. Although safety is seen as a priority amongst stakeholders, it should also be clear that safety is a first considerations and is not unnecessarily or unconsciously subordinated. As Hillestad et al. (1993) recommended: organizations associated to airports should set "safety first". Given this general recommendation, recommendations are provided for the identified challenges and opportunities.

1. Opportunities on improving safety by modifying Standards and Recommended Practices (SARPs).

Recommendation 1: By a lacking definite definition of through taxi-routes, airports are enabled to make usage of the 'greyness' of the definition of apron taxiways for the sake of handling increasing traffic demand, undervaluing the impact on safety. Therefore, it is recommended to investigate possibilities of introducing a maximum length of aircraft stand taxilanes - eliminating the discussion on through taxi-routes.
SHELL interaction(s): Software
Deming step: Act
Implementation stage: Minimization

Recommendation 2: No visual differences can be seen by pilots on the distinction between apron taxiways and aircraft stand taxilanes: both have aircraft stands alongside, and differences in clearances are too small to be perceived optically.

Therefore, in order to increase awareness amongst pilots, it is recommended to investigate distinctions in visual aids for taxiways/apron taxiways and aircraft stand taxilanes; for example different colors of center line markings, dashed center line markings and different colors of center line lights.
SHELL interaction(s): Environment
Deming step: Act
Implementation stage: Minimization

Recommendation 3: It is suggested to explore possibilities of introducing a maximum speed by the airport operator. Introducing airport-specific maximum taxi speeds enables defining a difference in maximum taxi speeds between taxiways and taxilanes, increasing the effectiveness of used decreased clearances at taxilanes, since it increases certainty on lower taxi speeds.
SHELL interaction(s): Software/Environment
Deming step: Act
Implementation stage: Minimization

2. Opportunities for improving taxiway system's safety assessment techniques.

Recommendation 1: To quantify safety of taxiway systems, it is recommended not to only use accidents and serious incidents; Also incidents of lower severity categories should be taken into account. Therefore, the measurement method as proposed in Section 4.2 might be used. However, the weight factors are not yet determined and therefore require further research.
SHELL interaction(s): Software
Deming step: Act
Implementation stage: N/A

Recommendation 2: For assessing the safety within taxiway system, it is recommended to use the sustainable safety vision. In the case-study of this research, the vision prove to be helpful in identifying vulnerabilities in taxiway systems. Besides, the vision of sustainable safety might be used in (re)designing taxiway systems.
SHELL interaction(s): Software
Deming step: Do
Implementation stage: N/A

Recommendation 3: The current occurrence reporting system (as defined by the European Union (2014)) causes limitations for investigations, leading to the following recommendations: Firstly, it is recommended to make reporting in English mandatory, making (automatic) analyses through word processors easier possible. Secondly, although occurrence categories in the reporting system are conform the by ICAO defined categories of accident and incidents, since 'incident' is one of the possible options within the occurrence category, only a limited number of occurrences are defined as one of the five incident sub-categories. Therefore, it is recommended to abolish 'incident' as one of the options and provided a clear definition of the incident sub-categories to reporters. Thirdly, analyzing the occurrence report data for black spots in a taxiway system unveiled difficulties, since the location field within the occurrence report data only contains up-to the level of the aerodrome. Therefore, an additional report field is recommended, containing a specific location on aerodromes. Alternatively, pointing the location at a map generating coordinates of the occurrences would be valuable.
SHELL interaction(s): Software/Hardware/Liveware
Deming step: Act
Implementation stage: N/A

7.5 FURTHER RESEARCH

Next to the previously listed recommendations, also a number of recommendations for further research are provided:

- In Section 4.2, a measurement method for safety of taxiway systems was proposed. However, the weight factors are not yet determined. Hence, further research on these weight factors is recommended.
- One of the often referred to contributors of increasing safety is 'complexity'. However, using the term 'complex' in relation to taxiway systems requires carefulness: before identifying the system as complex, it should be considered in which perspective it is regarded and the legacy of the airport should be taken into account as well. Moreover, in case the terminology of complexity is used, it can be split up in two components: infrastructural and operational complexity. Therefore, it is recommended to perform more research on (quantifying) the complexity of taxiway systems.
- Within the taxiway system of AAS, a high number of occurrences seems to be reported in areas were NaBo and WiBo aircraft merge and mix. Therefore, it is recommended to perform further research on the impact of mixing NaBo and WiBo aircraft in taxiway systems.
- In the end, to support decision making and provide figures on saturation of taxiway systems, it is recommended to perform further research on quantifying taxiway systems' capacity. In Section 4.3 a first step on measuring capacity was made by proposing a multi-function.

8 DISCUSSION AND REFLECTION

This final chapter evaluates the results, conclusions and research method, which have been explained earlier.

This study considered a set scope of taxiway systems, based on the in Chapter 3 provided definitions. However, as concluded, many aspects within the airport system are related to each other, implying limitations to this research. One of the most important type of occurrences related to safety which was not part of this research are runway incursions. Although a lot of research is already being performed on this specific topic, filtering out runway incursion from the occurrence report data might have caused limitations: for example taxiway N2 showed a relative high number of occurrence reports. Yet, in case runway incursions would not have been filtered out, this number might have been significantly higher.

In the case study of Amsterdam Airport Schiphol (AAS) the scope is limited to 'handelsverkeer', thereby excluding General Aviation (GA). However, the black spot analysis showed high numbers of occurrence reports in the GA-area of AAS (Schiphol East), which thus have not been researched.

Moreover, the pushback and docking process on aprons were outside the scope of this research, although overlap to the taxiway system is present in these processes. Nonetheless, during interviews, several stakeholders referred to these processes. As shown in the activity diagram of the Taxi-In process at AAS (Figure 5.17), in case no Visual Docking Guidance System (VDGS) or marshaller is available at the stand, inbound taxiing aircraft have to wait on the taxiway system until either the VDGS is switched on or a marshaller is present, before entering the stand.

Besides, interviewees referred to the communication during pushback. Currently, communication during pushback at AAS is organized as shown in Figure 8.1.

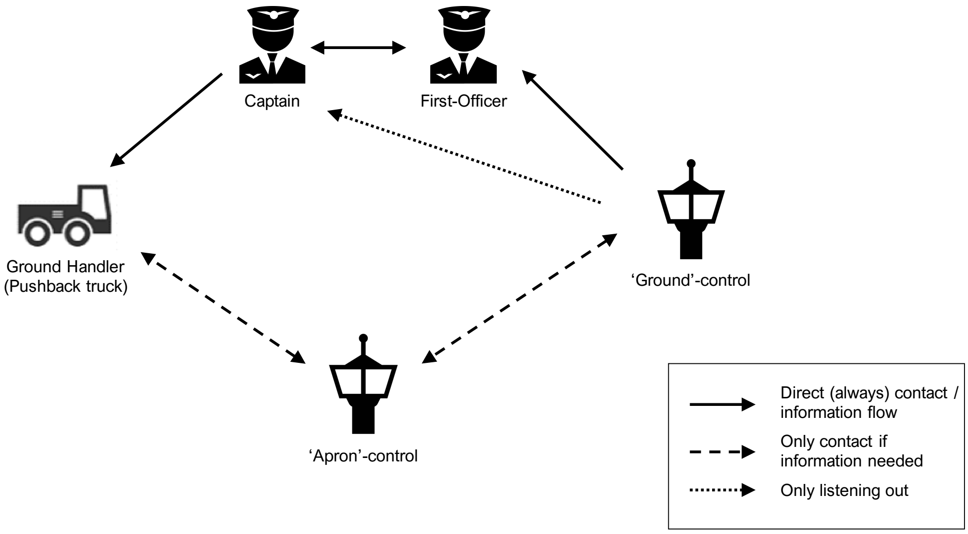

Figure 8.1: Current communication flows during pushback at AAS

In the current situation, 'Ground'-control starts by providing the pushback clearance to the First-Officer. Next, 'Ground'-control provides the pushback instruction to the First-Officer, who passes on the instruction to the Captain. The Captain also listens out the 'Ground'-control frequency to ensure correctness of the provided instruction. Thereafter, the Captain informs the Ground Handler about the pushback instruction via the intercom. However, the Ground Handler, next to listening to the Captain via the intercom, also listens out 'Apron'-control for eventual additional instructions. Also, in case the Ground Handler is unable to understand the captain's instruction (according to interviewees regularly the case with foreign carriers), the Ground Handler will ask 'Apron'-control to provide the instruction. In that case, 'Apron'-Control contacts 'Ground'-control and asks for the pushback instruction and then provides it to the Ground handler. Pilot 3 wonders whether the current situation is optimal, since the instruction information makes a detour and eventually requires additional communication.

In Section 7.3 it is recommended to consider a re-organization of the Air Traffic Control (ATC)-system for movements on the surface of the aerodrome: upgrade 'Apron'-control to become part of Air Traffic Control the Netherlands (LVNL) and let them guide and control all traffic within the bays (eventually split up in two or more areas), such that 'Ground'-control can focus on all traffic (including towed-traffic) on through-routes within the taxiway system. In that case, 'Apron'-control will also be responsible for pushback clearances and instructions.

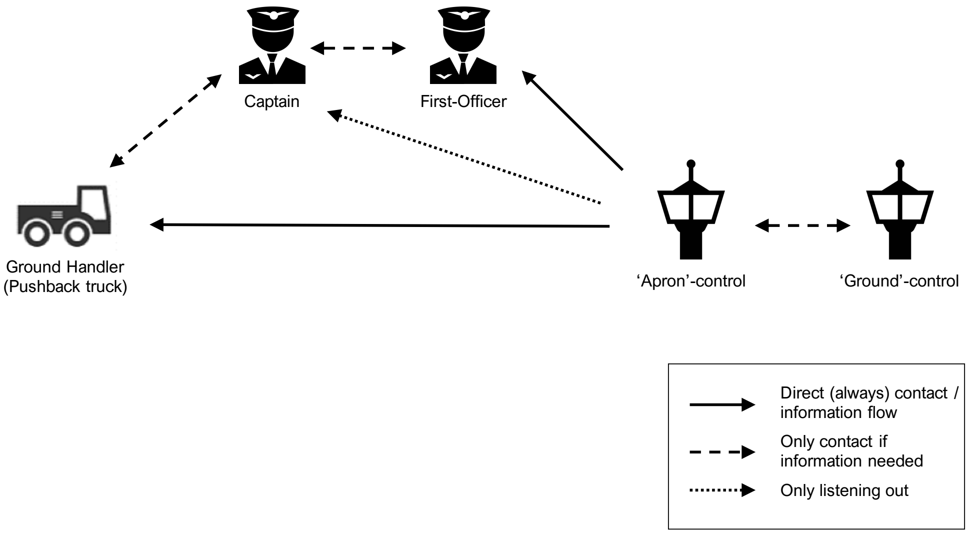

Figure 8.2: Possible communication flows during pushback at AAS with re-organized ATC-system

Figure 8.2 shows the possible communications flows regarding pushback within the re-organized ATC-system. To prevent unclear communication between the flight crew and the Ground Handler, it is suggested to let 'Apron'-control provide the pushback instruction to both the First-Officer and the Ground Handler. For pushbacks, mutual coordination between 'Apron'- and 'Ground'-control is only required in case 'Apron'-control detects an arriving aircraft taxiing towards a bay where also a departing aircraft is ready for pushback. Besides, the Captain will only have a monitoring function during pushback

Hence, although the pushback process is outside the scope of this research, the suggested re-organization of the ATC-system at AAS provides possible improvements and advantages for pushback processes as well by solving the concerns of Pilot 3. Also Pilot 4 expects advantages of the proposed system for certain locations at AAS.

Within the interviews, LVNL is not represented, although they are an important stakeholder in the taxiway system at AAS as ATC-provider. Despite various attempts, the organization was not open for an interview. To pursue a comprehensive view, Air Traffic Controllers (ATCOs) not related to AAS were interviewed (see Section 2.2). Besides, one 'Apron'-controller of AAS was interviewed. However, as mentioned, currently 'Apron'-control is not part of LVNL, but is part of Royal Schiphol Group.

Another limitation of this research is the extensive number of (required) assumptions in the stochastic model, which was used to develop a heat map. Either separate assumptions or the complete heat map require(s) validation based on historical ground movement data. Unfortunately, this data was not available for this research. The unavailability of the data also was the reason to use observations to base the assumptions on. However, no notes or reports of these observations were made, limiting the validity of the research method.

As already mentioned, the used occurrence report data shows limitations. Since legislation on reporting and reporting behaviour has changed over the years, the occurrence report data does not permit any definite conclusions to be drawn. Besides, the quality of reports is not equal and constant: the level of detail amongst reports differs depending on the reporters, decreasing the reliability of conclusions.

In this research only occurrence report data for AAS was used. However, to place the found figures into perspective, data of other airports should be used to make comparisons amongst taxiway systems of airports. This was not done in this research due to time limitations, and since only AAS-related data was provided by the ILT for this research.

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Appendices

A SCIENTIFIC PAPER

This appendix provides a scientific paper on the safety analysis of the taxiway system of AAS through sustainable safety.

Assessing Airport Taxiway Systems on the Sustainable Safety Vision: the Case of Amsterdam Airport Schiphol

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Abstract

In line with the global Air Transportation System, Amsterdam Airport Schiphol (AAS) has seen growth for the last decades and reached the current limit of 500,000 annual movements. Growth is only allowed if this is demonstrable safely possible. However, the Dutch Safety Board exposed several safety risks within surface operations at AAS. In this paper, for the first time, a taxiway system is assessed on the - in road transport proven - vision of Sustainable Safety to provide new insights on safety within taxiway systems. Based on the the case-study of AAS, assessing taxiway systems on Sustainable Safety showed to be valuable. The assessment denoted challenges and opportunities, before the taxiway system of AAS qualifies for meeting the principles of Sustainable Safety. Consequently, various topics for further research were found.

Keywords: Taxiway System, Airport Surface Safety, Sustainable Safety, Amsterdam Airport Schiphol

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1. Introduction

For the last decades, the Air Transportation System (ATS) has been growing almost ceaselessly. This growth can also be found at Amsterdam Airport Schiphol (AAS), where the number of passengers has grown from 37 million passengers in 1999 up to 71.7 million passengers in 2019 [1]. Accordingly, the number of aircraft movements increased from 393,606 (1999) to almost 500,000 in recent years, thereby reaching the current limit of allowable number of annual movements[1]. The Dutch Government underpinned the economic importance of AAS as major airport in The Netherlands, offering connectivity to the world. Yet, the Government stated that growth will only be allowed providing that a set of defined criteria is met [4]: (1) Growth shall be demonstrable safely possible; (2) the (noise) nuisance for AAS's neighbours shall be reduced, especially during night-hour operations; (3) the emission of CO_2 shall be reduced; and (4) growth shall be used as much as possible to support the network quality of AAS.

The first criterion might cause challenges. Both Hillestad et al. [5] in the 1990s and more recently the Dutch Safety Board [6] concluded that the past growth had an adverse effect on the safety of airside operations at AAS. Both investigations were performed in response to (a series of) incidents at the airport. The investigations exposed several safety risks and provided recommendations which should be tackled to ensure safe operations in the future. Frequent runway configuration changes result in a complex traffic handling process. Consequently, Air Traffic Controllers (ATCOs) operate under high workloads. In addition, the large number of taxiways, runway exits and entries (including Rapid Exit Taxiways (RETs)) and relative runway orientations rise the safety risk [6]. Moreover, it was concluded that runway incursions and confusion of flight crews might be caused by the large number of taxiways and the use of RETs for entering the runway. Since runway incursions are considered to be a separate topic of study, this research focuses on airport surface safety within taxiway systems, excluding runway incursions. Although airport surface safety has been researched (e.g. [7], [8]), the - in road transportation proven - vision of *Sustainable Safety* has not been used for assessing taxiway systems before. To provide new insights on safety within taxiway systems, the by the Institute for Road Safety Research (SWOV) [9] developed Sustainable Safety vision is used to assess the taxiway system of AAS in this research.

Taxiway systems are designed and developed following the Standards and Recommended Practices (SARPs) as developed in Annex 14 by the International Civil Aviation Organization (ICAO) [10]. Within Annex 14, safety can be seen as the thread. For European airports, including AAS, the European Union Aviation Safety Agency (EASA) [11] defined similar specifications. Since the specifications of EASA are based on the more globally applied ICAO's Annex 14, this research uses Annex 14 as reference. Besides, to limit the scope of the research, only commercial air traffic is taken into account for the case-study.

In the next section, the vision of Sustainable Safety is described and translated for taxiway systems. Next, supportive analyses are provided in section 3. Afterwards, section 4 assesses the taxiway system of AAS on Sustainable Safety. Lastly, conclusions and recommendations are provided in section 5.

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[1] Until 2021, the growth of AAS is limited to a number of 500,000 annual aircraft movements (one movement means one takeoff or one landing). This number includes commercial air traffic (referred to as 'handelsverkeer') and does not include General Aviation (GA) and technical air traffic [2, 3].

2. The vision of Sustainable Safety

In 1992, along with Sweden, a vision on sustainably safe road traffic was firstly conceptualized in The Netherlands. The goal of Sustainable Safety is to achieve safety by systematically reducing underlying risks of the traffic system. Hereby, the vision focuses on human factors [9], in line with the by ICAO [12] defined approaches to safety within the aviation industry. The awareness that human factors are important when it concerns road safety has been accepted for decades [13]. Already in 1979, Treat et al. [14] stated that people are not only physically vulnerable, but also fallible: they make errors. Therefore, human characteristics are of large importance when concerning safety. Amongst other industries, also in aviation it has been recognized that rather than adapting people to a system, the system should be adapted to people's abilities and desires, which is also known as 'safety by design' [9]. Sustainable Safety as described by SWOV [9] has not been applied to taxiway systems before, although taxiway systems show similarities to road systems. Below, the five road safety principles are described and a translation to the taxiway system is made.

Three of the five principles are *design principles*. In accordance with the **functionality** design principle, a network ideally has a hierarchical and functional structure of traffic functions. In a road network, this structure is built up of three categories of roads:

- *through-roads* (flow function on road sections and across intersections)
- *distributor roads* (flow function on road sections and exchange function at intersections)
- *access roads*[2] (exchange function on road sections and at intersections)

In taxiway systems, this is split up in two major categories. For the flow function, ICAO defines *taxiways*, which are intended to provide links on the aerodrome. For the exchange function, ICAO defines *aircraft stand taxilanes*, which intended to exclusively provide access to aircraft stands.

For both categories, ICAO [10] defined different separation distance design criteria. The differences are based on the assumption that flight crews are more focused on aircraft stand taxilanes, as they will shortly access an aircraft stand, and therefore the aircraft's speed is lower as well. Additionally, SWOV [9] mentions that in cases where mono-functionality cannot be realized in the short term (referred to as 'grey roads'), efforts should be made to achieve (temporary) results that provide adequate safety by focusing on the most vulnerable user. In taxiway systems, 'grey roads' are referred to as *apron taxiways*.

The **(Bio)mechanics** principle implies limiting differences in speed, direction, mass and size, and giving road users appropriate protection. Accordingly, fast-flowing traffic should either physically, or timewise be separated from slow moving traffic, traffic travelling in opposite direction, traffic with a substantially different mass or width, and hazardous obstacles. Within taxiway systems, generally no speed limits are defined, as these are aircraft and/or airline specific. Whether opposite directional flows are separated depends on the airport layout: at larger airports, directional taxiways may be used to separate flows, where at smaller airports separation is solely done by Air Traffic Control (ATC)-guidance. Separation of vehicles with substantially different masses on airport surfaces are found in the separation of aircraft from service vehicles. Service vehicles are generally only allowed on service-roads and not on taxiways, unless otherwise instructed by ATC. Besides, several airports handle (small) GA flights in separate areas on the aerodrome. Separation of hazardous obstacles is achieved through clearances.

In accordance with the **psychology** design principle, the design of a traffic system environment is well-aligned with the competencies and expectation of its users. Hence, the information from the traffic system should be perceivable, understandable ("self-explaining"), credible, relevant and feasible. Accordingly, safe road behaviour is ideally as little as possible subject to individual users' choices. Transferring information to road users is done by the road layout, the road environment, traffic signs and regulations. Within taxiway systems, no differences in layout are present. The environment only differs for aircraft stand taxilanes, which are located along aircraft stands. Yet, no environmental distinction between apron taxiways and aircraft stand taxilanes can be seen. Traffic signs in taxiway systems are referred to as visual aids.

The other two principles are *organizational principles*. **Responsibilities** should be allocated and institutionally embedded in such a way that they optimally support maximum safety as a result for all users. Within road networks, national governments are generally responsible for the system in the first place, and as such carries the ultimate responsibility with the inherent task to protect its citizens while simultaneously providing transport opportunities. Since taxiway systems are not necessarily part of the public space and airports might be privatized, it is questionable whether national governments have the ultimate responsibility for taxiway systems too. Nonetheless, all involved stakeholders should take their responsibility in maximizing safety within taxiway systems.

The final principle supports continuously **learning** and **innovating**. Therefore, the principle refers to the Deming cycle [15], starting with the development of effective and preventive system innovations based on knowledge of causes of occurrences (*Plan*). By implementing these innovations (*Do*), by monitoring their effectiveness (*Check*) and by making the necessary adjustments (*Act*), system innovation ultimately results in fewer occurrences. To support learning from past events, occurrence reports are collected in a central database by the European Union [16] if it is related to: (1) the operation of the aircraft (e.g. collision-related); (2) technical conditions, main-

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[2] In Sustainable Safety, an access road is a road for local access. It is not the type of 'access road' that is used in some countries to provide access to a major destination such as a port or an airport, most often a through-road [9].

tenance and repair of the aircraft; (3) air navigation services and facilities (e.g. (near) collisions, specific occurrences or operational occurrences); or (4) aerodromes and ground services (e.g. related to ground equipment). Within The Netherlands, the Inspectie Leefomgeving & Transport (*Human Environment and Transport Inspectorate*) (ILT) is responsible for collecting occurrence reports.

3. Analysis of AAS

To support the assessment of AAS's taxiway system to the described vision, several other analyses are performed [17]. Major findings of these analyses are provided in this section.

3.1. Airport configuration

The configuration of AAS can be seen as a legacy of Jan Dellaert. His 1950s master plan for AAS formed the basis for the airport as it is known nowadays. Dellaert's plan, with a tangential runway system and a central traffic area, enabled the airport to operate at maximum capacity regardless of the wind direction. The by Schiphol and Royal Dutch Airlines (KLM) further elaborated plan was based on 100,000 annual movements and 2 million passengers around the 1970s/1980s [18]. As a result of the tangential runway system, the main taxiways (A, B, Q) create a 'ring road' around the central terminal area. In Figure 6, to be found at the end of this paper, an overview of the runways and major taxiways of AAS is presented.

3.2. Stakeholder Interviews

To gain insights from AAS stakeholders and to support findings from other analyses, nineteen interviews were conducted amongst pilots, airport authorities, ATCOs, ground handlers, and airport consultants. The experienced problems at AAS that were most referred to are: (1) the regularity of non-standard operations, (2) difficulties for rare visitors and (3) the difficulty of the area around the threshold of runway 24 [17].

3.3. Heat Map

A heat map of traffic flows, with annual movements per node, is created to gain insights on traffic intensities in the taxiway system. Since historic data on traffic movements within the taxiway system of AAS was not available for this research, a stochastic model is developed to generate the heat map [17].

Based on the heat map of AAS (Figure 1), busy areas appear to be around the central area (taxiways A and B) and taxiway V - to and from the Polderbaan (18R/36L). The high number of taxi movements on taxiway V can be explained by the high preference of usage of the Polderbaan within the by regulations defined runway configurations [19].

Within the central area of AAS, on the 'ring road' of taxiways, the traffic demand is relatively high on taxiways A and B, parallel to the Aalsmeerbaan and Kaagbaan. The busiest area within the taxiway system at AAS is the intersection of RET S4, taxiway B and taxiway A4. The main traffic flows on this node are: (1) Traffic vacating the Kaagbaan (06) via S4 (primary RET) or earlier; (2) arriving traffic from taxiway Q, taxiing towards the B-, C- or D-pier; and (3) departing traffic from the A-apron and B-pier routing towards the Kaagbaan (24) or North.

Figure 1: Heat map of traffic demand in the taxiway system of AAS

Moreover, all nodes around the threshold of runway 24 (Kaagbaan) showed to be crowded. In this area, many conflicting traffic flows occur: (1) Traffic departing from the Kaagbaan (24), taxiing towards one of the entries from all directions; (2) traffic departing from the A-apron, B-pier or C-pier taxiing to the North over taxiway B; and (3) arriving traffic for the C/D-bay from all directions.

Amongst the busiest nodes are also the Eastern and Western end-nodes of taxiway Q, showing this taxiway's importance within the taxiway system. Yet, this high demand does not necessarily cause problems since traffic flows on taxiway Q are generally unidirectional. Nonetheless, conflicting traffic flows may occur on the end-nodes.

3.4. Occurrence Report Data

For this research, occurrence report data related to the taxiway system of AAS of the past decade is provided by the ILT from the European central database. To enable more detailed analysis within taxiway systems, nine specific categories are defined based on the occurrence categories [16] as mentioned in section 2:

- ***ATC***: Deviation from standard procedures by ATC;
- ***Lacking ATC***: Guidance of ATC is lacking;
- ***Flight Crew***: The flight crew deviates from the instruction of ATC or a standard procedure;
- ***Other vehicle***: An occurrence of an aircraft with another vehicle (no aircraft), e.g. tow movements on taxiways or service vehicle or ambulances on intersections of taxiways with service roads;
- ***Failure***: A failure within the taxiway system, such as Foreign Object Debris (FOD);

- ***Taxi speed***: The flight crew exceeds the maximum allowed taxi speed;
- ***Technical issue***: A technical issue with the aircraft;
- ***Pushback/docking***: An occurrence during pushback or docking at the stand.
- ***Other***: All other occurrences.

Each report is categorized in accordance with the above defined categories. Occurrences categorized as *technical issue, pushback/docking* and *other* are outside the scope of this research and are therefore not considered. In the end, the used data set contains 1,766 occurrence reports. Based on the number of movements in the time period of the data set [1], on average 3.7 occurrences per 10,000 movements within the taxiway system at AAS were encountered in the past decade. Figure 2 shows an increasing trend in the number of annual occurrences per 10,000 movements. A stabilization is seen after 2016, potentially suggesting positive results of the initiated Integral Safety Management System (ISMS). However, the occurrence report data does not permit any definite conclusions to be drawn regarding the number of occurrences, since legislation on reporting and reporting behaviour has changed over the years [20]: The reporting regulations by the European Union [16] are implemented by the National organizations between 2014 and 2017.

The majority of reports regards deviations by *flight crews* from instructions of ATC or from standard procedures (on average > 50%). Thereafter, the major contributing occurrence category (on average 27%) regards occurrences of aircraft with *other vehicles*, such as towing movements or service vehicles. Besides, a large increase in number of occurrence reports on *taxi speed* exceeding of the airline-specific maximum taxi speed is seen, which might (partly) be caused by increasingly monitoring taxi speeds by airlines. Notwithstanding, several causes for over-speeding can be found in the report data. Partly, over-speeds were performed by the flight crew on request of ATC. Three reported reasons for this request are: (1) to let the aircraft overtake a preceding aircraft to adjust the planned departure sequence, (2) to cross runway 18C/36C at intersection W5 before the runway is opened, or (3) to expedite vacating a runway after landing because of another runway on short final, which is also recognized by interviewed pilots. Moreover, a number of over-speeds were on request of the flight crew, primarily based on the pressure of arriving on time and meeting the schedule. In the end, the majority of over-speeds were unconsciously caused by the flight crews and were only momentary.

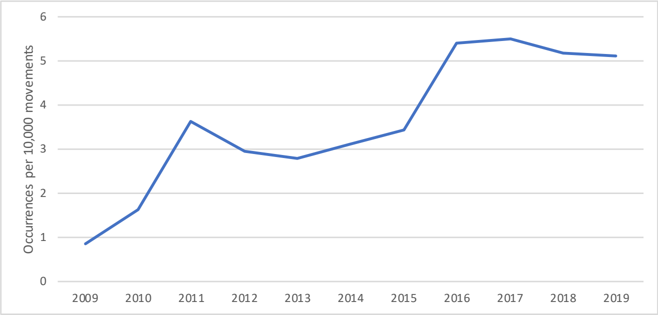

Figure 2: Number of occurrences per 10,000 movements

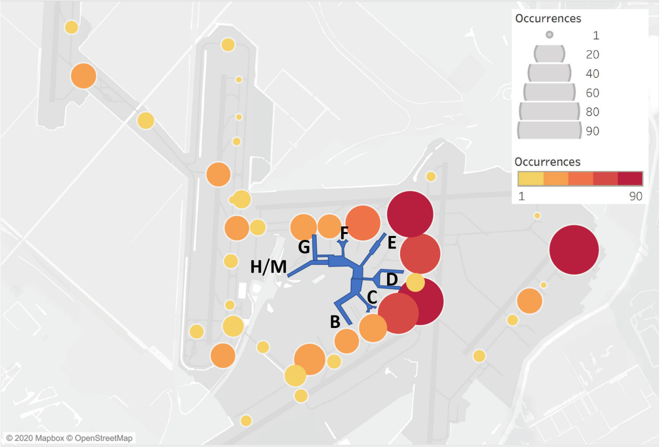

Figure 3: Black spots and zones of the taxiway system at AAS

The large share of occurrences related to deviations by *flight crews* seems a superficial observation. Flight crews are given the majority of the blame. Yet, to improve the system, a shift in focus is needed from individual blame to the system and related processes [21].

3.5. *Black Spot Analysis*

Although 846 of the 1,766 occurrence reports did not contain a location indication, a black spot analysis is performed. Black zones [22] were used since in a large part of the taxiway system (especially along taxiways A and B) intersections are located close to each other. Figure 3 shows the black spots and black zones of the taxiway system of AAS, from which several things can be concluded. Firstly, the largest black zones appear to be the area close to the threshold of runway 24, which also was identified as one of the busiest areas. Secondly, a high number of occurrences are reported in the North-East area of the 'ring road'. A large number of runway exits/entries of two different runways are situated close to each other in this 'corner' of AAS's central area. Besides, the major remote holding apron is located in the middle of the area, as well as three bays.

4. Sustainable Safety of AAS

As mentioned before, Dellaert's master plan formed the basis of AAS's tangential runway system. The 'ring road' of taxiways, parallel to the runways around the central traffic area, creates a boundary for expansion of piers. As a result, piers and adjacent aircraft stands are located very close to - and even along - through taxi routes on taxiways A and B, which users experience as undesirable and which is not in line with the design principles of sustainable safety. Furthermore, during taxi-in after landing, aircraft regularly have to hold due to unavailability of gates and stands.

In accordance with the **functionality** design principle, a network should have a hierarchical and functional structure. All bays around piers at AAS are designed by using *aircraft stand taxilane separation distances* and all other taxiways using *taxiway separation distances*. However, as mentioned before, also ‘grey roads’ [9] can be identified, namely apron taxiways. It was found that the definition and distinction of apron taxiways and aircraft stand taxilanes is debatable. The only difference in definition is that aircraft stand taxilanes exclusively provide access to aircraft stands, whereas apron taxiways (next to providing access to aircraft stands) also provide through taxi-routes. Since no strict definition of through taxi-routes is provided, airports could use the ‘greyness’ of the definition for the sake of handling increasing traffic demand, possibly undervaluing the impact on safety, by easier defining a taxiway as aircraft stand taxilane (requiring less horizontal spacing). Hence, the usage of the ‘greyness’ of the definition tends to be the result of ‘practical drift’ [23]: the system, procedures and regulations are designed in a theoretical environment with implicit assumptions (slower taxiing aircraft at aircraft stand taxilanes), which might differ in practice. Nonetheless, Figure 4 shows the clearly identified apron taxiways at AAS. These are designed with taxiway clearances, but also provide access to stands.

Two debatable aircraft stand taxilanes are shown in Figure 5. Within the left red circle in Figure 5, the currently as aircraft stand taxilane designed taxiways A19E and A19W are shown as apron taxiway. These taxiways are primarily used by Narrow Body aircraft (NaBo) aircraft to and from the H/M-pier, where taxiway A19C is used by Wide Body aircraft (WiBo) aircraft for access to G-stands. Hence, along the G-pier, taxiways A19E and A19W provide a through-route to the H/M-pier and taxi speeds might be expected to be relatively high for taxilanes.

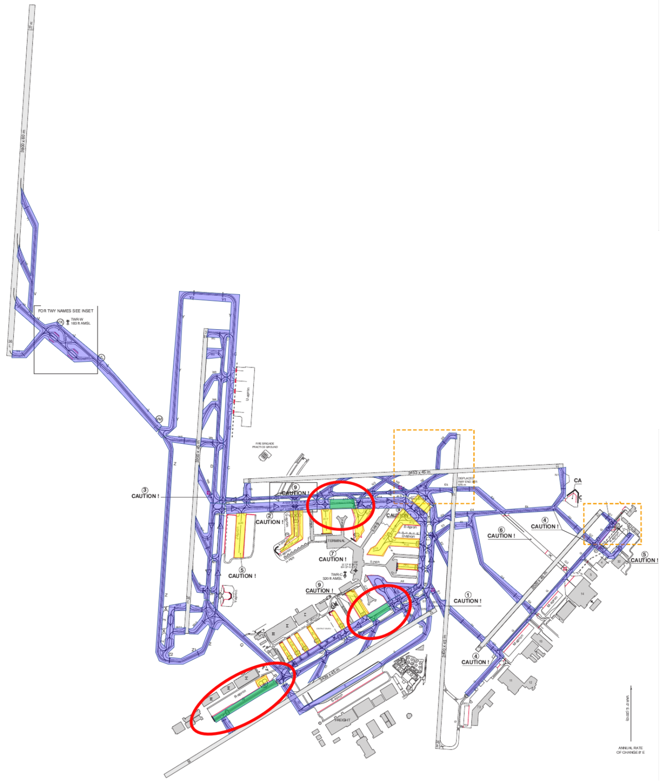

Figure 4: Taxiways (blue), Apron taxiways (green, red circled) and Aircraft Stand Taxilanes (yellow) at AAS

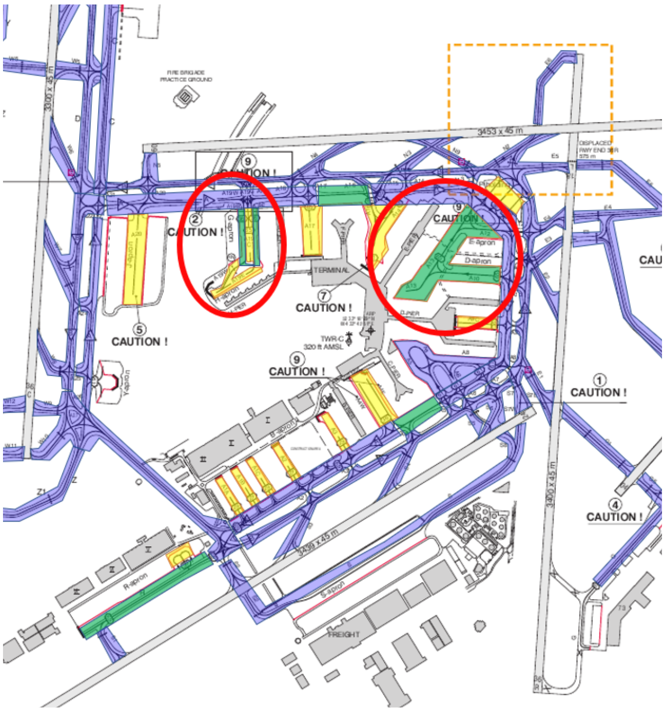

Figure 5: Debatable apron taxiways (green, red circled)

Within the right red circle in Figure 5, taxiways A10 and A13 are shown as apron taxiway. Although the taxiways are primarily used for accessing stands, pilots stated that they are seduced to taxi at relatively high speeds due to the extensive length of the bay. Therefore, it is suggested to conduct further research on introducing a maximum length of aircraft stand taxilanes.

The **(bio)mechanical** design principle advises separation of road users with differences in speed, direction, mass and size. No airport-specific maximum taxi speed is defined. Speed limits are airline-specific. Nonetheless, most commercial airlines use 30 *kts* as maximum taxi speed on straight taxiways. Pilots also stated that they generally taxi with lower speeds within the bays - which is in line with the design criteria for taxilanes. However, they also mentioned that on long taxilanes, speeds are still relatively high. Putting the aforementioned into perspective of other transportation systems, it can be considered as exceptional that there is no maximum speed for given infrastructure on airports. Within road and rail transport, the infrastructure-operator defines maximum speeds for specific parts of infrastructure in order to ensure safe operations. Therefore, it is suggested to explore possibilities of introducing a maximum speed by the airport operator. Additionally, introducing airport-specific maximum taxi speeds enables defining differences in maximum taxi speeds between taxiways and taxilanes, increasing the effectiveness of used decreased clearances at taxilanes, since it increases certainty on lower taxi speeds.

Separation in direction at AAS is primarily present on taxiways A and B with defined directions. Yet, pilots stated that ATC regularly deviates from these directions. Moreover, currently taxiway Q might be used in both directions alternately at the same time, increasing the chance of traffic standing opposite each other in case of inattention of either ATC or flight crews. Known crashes in the rail transportation (e.g. Westerpark Amsterdam with almost 200 injuries and 1 fatality) underpin the importance of mitigating the risk of opposite traffic [24]. Therefore, a parallel taxiway South of taxiway Q is currently being planned and constructed, to complete the double 'ring-road' of taxiways around the central area of AAS with separated directions [25].

Aircraft of different masses and sizes are partly separated in the taxiway system at AAS. The (smaller and lighter) GA-aircraft are handled at Schiphol East, separated from all commercial traffic (generally medium and heavy). Within the central commercial traffic area of AAS, also a separation of NaBo and WiBo can be seen: On the B-, C-, and H/M- pier, only NaBo aircraft are handled, on the D-pier a mixture of NaBo and WiBo aircraft is handled, where on the E-, F- and G-pier primarily WiBo aircraft are handled. Looking at the black spot analysis in Figure 3, keeping this separation in mind, it can be seen that the largest black spots and black zones are found in the area where NaBo and WiBo merge and mix. Therefore, it is suggested to conduct further research on the impact of mixing NaBo and WiBo aircraft in the taxiway system.

In accordance with the **psychology** principle, the system shall be "self-explaining". Hence, transferring information to users shall be done through the layout, the environment, visual aids and procedures. At several intersections in the taxiway system at AAS, information signs are used to indicate directions, as well as markings showing directions. However, no visual differences are seen by pilots on the distinction between apron taxiways and aircraft stand taxilanes. Both have aircraft stands along-side, and differences in clearances are too small to be perceived optically. Therefore, in order to increase awareness amongst pilots, it is suggested to investigate distinctions in visual aids for taxiways/apron taxiways and aircraft stand taxilanes; e.g. different colors of center line markings, dashed center line markings and different types or colors of center line lights.

Besides, the level of "self-explaining" is questionable within the taxiway system at AAS given the noticeable, and amongst pilots and airport representatives recognized, large number of deviations from standard procedures by both flight crews and ATC. It is also acknowledged that this might cause safety risks. By repeatedly deviating from procedures and standards without hazards, users are inclined to make the deviation a habit and taking the risk of deviating is accepted, also known as *normalization of deviance* [26]. Besides, once deviation is ingrained, rooting it out is challenging [21]. It is recommended to further investigate and reconsider the standards and procedures at AAS.

Moreover, interviewed pilots felt that for flight crews who visit AAS for the first time (or rarely), taxiing within the taxiway system might be very challenging due to the special conditions and usage of standard taxi routings. The airport's Operations department indicated to receive similar feedback on non-AAS based carriers having more difficulties resulting them in stopping more often and requiring more communication with ATC. It is acknowledged that investigating differences amongst (reported) occurrences of regular and irregular AAS visitors can be difficult in an international perspective[5]. Nonetheless, it is recommended to do so and treat rare visitors as vulnerable users, providing them special attention during operations.

Both Hillestad et al. [5] and the Dutch Safety Board [6] recommended to establish an organization in which stakeholders cooperate to improve safety management at AAS. Successively, the ISMS was founded, wherein Royal Schiphol Group joined forces with airlines, ATC, ground handlers and refueling services to take an integral approach to the management of safety at AAS [27]. Besides, the Dutch Government was recommended to take ultimate **responsibility** for the safety of air traffic at and around AAS.

Despite the tangential runway system, the number of runway configuration changes at AAS is extremely high in an international context. Due to the tangential system, most changes are not weather based. Instead, 90% of the on average 18 daily configuration changes are related to noise regulations, resulting in a contradiction. The Dutch government requires AAS to follow up recommendations of the Dutch Safety Board [6] to reduce the daily number of runway configuration changes on the one hand, where on the other hand the Dutch government set the regulations on noise restrictions causing the high number of changes. The current situation tends to be an over-optimization for a single aspect, namely noise complaints from local residents. Moreover, where the Dutch Safety Board focuses on safety implications of this large number of daily configuration changes for the runway system, it should be recognized that a runway configuration change also impacts the taxiway system: each runway configuration results in a certain traffic flow of taxiing aircraft. Hence, each runway configuration change causes a different traffic flow within the taxiway system too, eventually leading to conflicting traffic flows. Besides, the large number of changes decreases the predictability for flight crews on taxi routings, making operations more complex. Consequently, the Dutch government should take responsibility for the extensive number of runway configuration changes at AAS related to noise.

The continuously **learning** and **innovating** loop is described by the Deming cycle [9, 15]. Gaining knowledge on causes of occurrences within the taxiway system of AAS is done by the ILT and Dutch Safety Board. However, room for improvement was found on the occurrence report data. In order to increase and improve opportunities of analyzing the occurrence data report, all reports should be written in English. Additionally, in order to increase accuracy of the black spot analysis, each report for occurrences within airports should contain a specific location indicator (e.g. intersection name or coordinate). Nonetheless, based on gained knowledge, Straube et al. [28] concluded that radio communication for guidance of aircraft during taxiing is near the capacity limit at many airports. Therefore, through the

Single European Sky ATM Research (SESAR) program, a surface traffic management concept was developed (*Plan*), which provides individual guidance to taxiing aircraft by automatically and progressively activating taxiway centerline lights along the route cleared by the ATCO: 'Follow the Greens' [29]. It has been validated that 'Follow the Greens' is a safer, quicker and greener surface traffic management concept [28]. At AAS, a project on Advanced Surface Movement Guidance and Control System (ASMGCS) has started. In this project, 'Follow the Greens' is presented as one of the alternatives. However, since fully implementing the technique requires extensive time and investments, first and early version of 'Follow the Greens' was installed at the intersection of taxiways W5, V, Y and Z as a proof of concept for AAS (*Do* and *Check*).

For the long term, the European Commission [30] defined topics for research in order increase safety and to reduce fuel consumption and emissions in surface operations at airports, which may also be valuable for AAS. Therefore, AAS shall keep abreast of the latest developments of this research and anticipate on eventual required adjustments on the taxiway system.

5. Conclusions and recommendations

In this paper, for the first time a taxiway system is assessed on the Sustainable Safety vision. Based on the case-study of AAS, assessing taxiway systems on Sustainable Safety showed to be valuable, by denoting challenges and opportunities towards improvements. Besides, it is expected that Sustainable Safety might be of added value in (re)designing taxiway systems. Human factors are the thread in the vision, with special attention for vulnerable users. In taxiway systems, rare visitors can be considered as vulnerable users, since they appear to have difficulties in operating within rather complex taxiway systems such as AAS.

On the operational safety of the taxiway system at AAS, the following can be concluded. The present taxiway system seems to be safe, yet shows challenges and opportunities for improvements. Looking at the legacy of AAS, Dellaert's 1950s master plan showed to deliver a solid airport system. The design, based on 2 million passengers and 100,000 movements in the 1970s/1980s, appeared to be able to handle 71.7 million passengers and almost 500,000 movements last year with extended terminal areas and piers in the by Dellaert designated central traffic area and one additional runway. Nonetheless, pressure from ATC on flight crews seems to increase and the present taxiway system tends to reach its safe operational limits, suggesting the system reached the 'wear-out' phase of the bathtub curve [31]. This might partly be caused by the 'practical drift' throughout the years. Hence, the assessment exposed various specific topics for further research. Below, recommendations are provided.

Due to a lacking strict definition of through taxi-routes in ICAO's Annex 14, it appears that the 'greyness' of the definition of apron taxiways is utilized by the airport in order to handle the peak traffic demands within the set systems boundaries. Therefore, it is suggested to conduct further research on introducing a maximum length of aircraft stand taxilanes. To increase the effectiveness of decreased separation distances at taxilanes, it is suggested to explore possibilities of introducing a maximum speed by the airport operator. Introducing airport specific maximum taxi speeds enables the implementation of a difference in speed limits for taxiways and taxilanes. Additionally, in order to increase awareness amongst pilots, it is suggested to investigate distinctions in visual aids for taxiways/apron taxiways and aircraft stand taxilanes; for example different colors of center line markings, dashed center line markings and different types or colors of center line lights.

Within the taxiway system of AAS, *normalization of deviance* [26] seems ingrained: both flight crews and ATC regularly deviate from standards and procedures. Past incidents in both aviation and rail underpinned the consequent safety risks of the deviance. To improve the system, a shift in focus is needed from individual blame to the system and related processes [21]. Therefore, it is recommended to investigate and reconsider the applicable standards and procedures at AAS. Moreover, it is recommended to investigate differences amongst (reported) occurrences of regular and irregular AAS visitors and investigate how to ensure safe operations for both, despite the acknowledged difficulties in international perspective [5].

From the black spot analysis it can be seen that the largest black spots and black zones are found in the area where NaBo and WiBo merge and mix. Therefore, it is suggested to conduct further research on the impact of mixing NaBo and WiBo aircraft in the taxiway system.

The 16 daily runway configuration changes at AAS related to noise regulations tend to be an over-optimization for a single aspect. Consequently, the Dutch government should take responsibility for the extensive number of runway configuration changes at AAS related to noise. A trade-off is recommended on the benefits of current noise regulations for local residents on the one hand, and side effects which include a consequently high number of runway configuration changes implying safety risks, on the other hand. In this trade-off, it should be acknowledged that runway configuration changes not only impact the safety around runways, but also within the taxiway system due to changes in traffic flows.

Despite the steps the aviation industry in The Netherlands has made towards an integral approach on safety, care must be taken to ensure that the taxiway system is not underexposed and that safety continuously remains a first considerations and is not unnecessarily or unconsciously subordinated.

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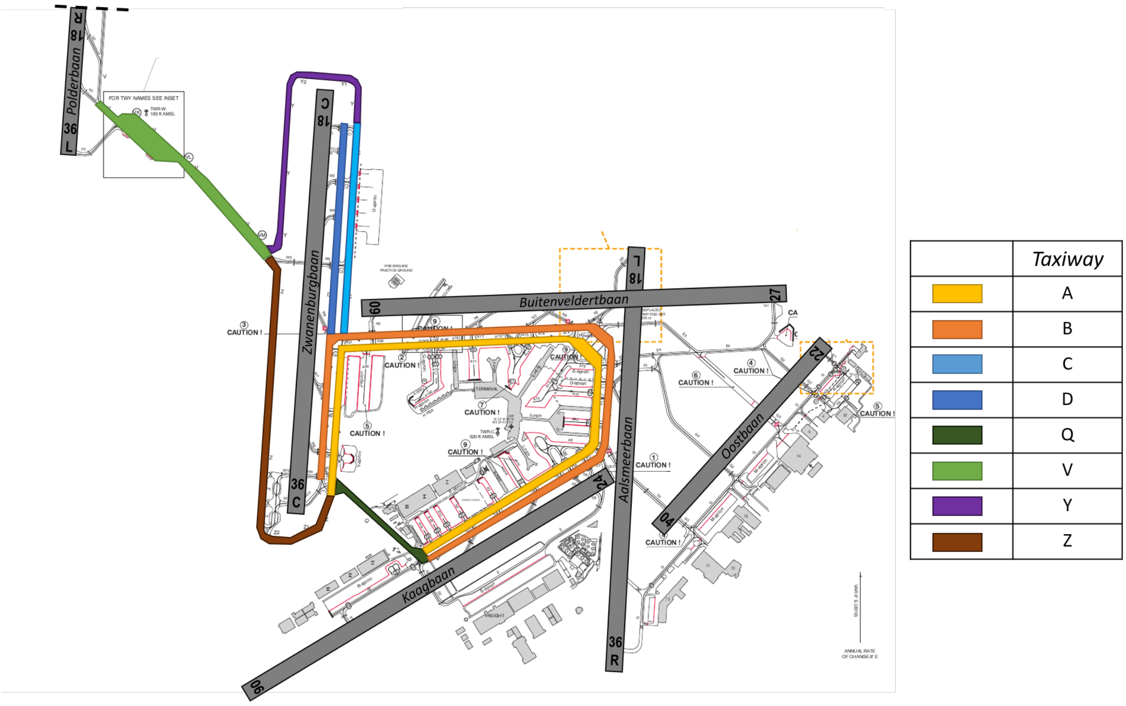

Figure 6: Runways and major taxiways at AAS

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B INTEGRAL DESIGN AND MANAGEMENT ANNOTATION CONTRIBUTION

This master thesis is - next to a partial fulfilment of the requirements for the Master of Science in Transport, Infrastructure and Logistics - a partial fulfilment of the requirements for the annotation *Integral Design and Management (IDM)*. The annotation aims for combining technical knowledge with engineering management skills, such as Systems Engineering (SE).

Hence, several IDM aspects were applied within this master thesis. This is mainly reflected in the usage of SE for the systematic approach to the subject: Through the V-model, the Air Transportation System (ATS) is split up in substructures and subsystems. One of the subsystems is the topic in this thesis: the taxiway system. Applying SE is attempted throughout the thesis by going from a higher to a lower/deeper level within the system-structure for each aspect. Besides, Unified Modeling Language (UML) was used to explore the processes within the taxiway system. By defining a use case diagram for the system, the use cases were identified, as well as the actors. For the major use cases, next, activity diagrams ('swimming lanes') were made. All this knowledge was gather during the 'Integral Systems Design' course. Moreover, a stakeholder analysis was executed, as learned during the 'Project Management' course.

Personally, I primarily chose to participate in the annotation to gain more insights and knowledge on Project Management and SE. Already during my Bachelor I got in contact with the IDM-annotation by attending the course 'Infrastructure Management' (CIE3380). In the first place the choice for this specialisation course was based on the goal to attend all infrastructural courses. Moreover, during several projects (e.g. the 'first year project' for the Integral Design course) and commissioner works within the study association, I figured out for myself that I liked working in a coordinating/management role.

After finishing the Bachelor of Civil Engineering, I got the opportunity to do an internship at Netherlands Airports Consultants (NACO) on geometric design of airports. During this internship, I was assigned a seat at NACO's office amongst the project managers. Also here, by hearing project managers talking about their job, I noticed my interest for this function in projects. This extra motivated my choice for attending the IDM-annotation.

By default, I followed the (mandatory) course 'Integral Systems Design' course (CIE4480). In this course, many aspects and advantages of using SE in projects were discussed and applied in assignments. Although during the course the discussed subjects seemed quite abstract, they became realistic and concrete while applying learned techniques within the 'Design Project' and within this thesis. The systematic approach as discussed during the course, as well as SE techniques such as use cases were applied during executed projects and within this thesis.

Besides, I completed the course 'Quantitative Methods for Logistics' (ME44205). In this course - as the name already suggests - quantitative methods are discussed for optimizing logistics. Through mathematical optimization models, an assignment of optimizing a production process was completed. I really enjoyed puzzling for the assignment and finding the practical objectives, constraints and convert them into a model. For me, this course was a nice addition to the set of IDM-courses, since optimization models are increasingly important in design management.

Based on my gathered interest in project management during my internship, I decided to attend in the course 'Project Management' (SPM8000) as well. In this course core elements of managing projects were discussed, such as stakeholder management, risk analysis and planning of projects.

As already mentioned, also within the 'Design Project' (TIL5050) I paid attention to IDM and SE aspects. For the project-course, a project-internship was executed within Rijkswaterstaat. They asked us to setup a joint smart mobility demonstration within a cooperation between the Chinese Research Institute of Highway (RIOH) and Rijkswaterstaat in Beijing (China) based on a Memorandum of Understanding.

Looking back on my study at the Delft University of Technology, I am glad with the choices I have made. With a technical basis from the Bachelor degree of Civil Engineering, broad knowledge on transportation from the Master degree of Transport, Infrastructure and Logistics, supplemented with the annotation of Integral Design and Management, I think I became a ζ-student during my studies: a β-student with technical knowledge, supplemented with societal γ skills.

C TAXIWAY DESIGN FIGURES

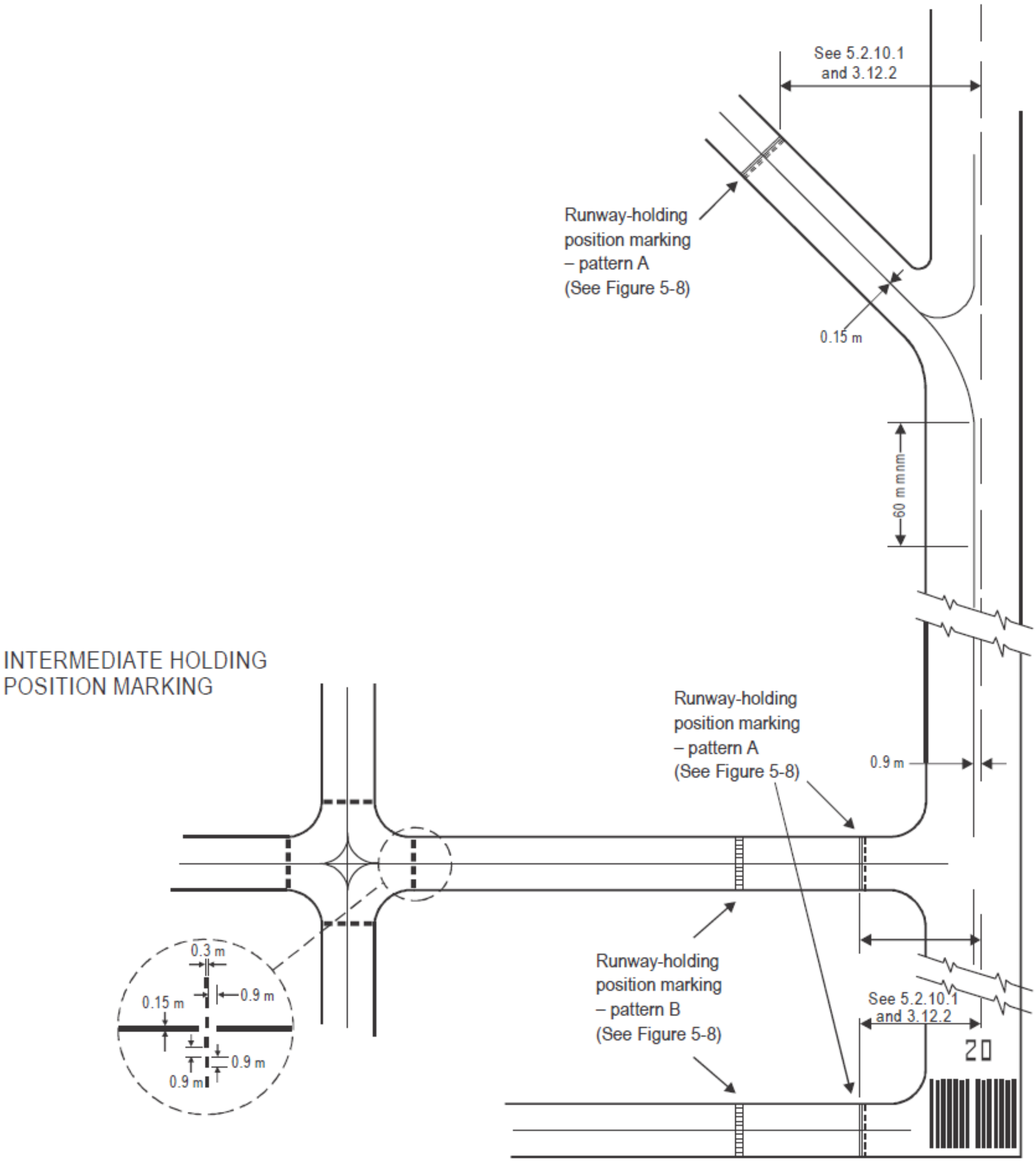
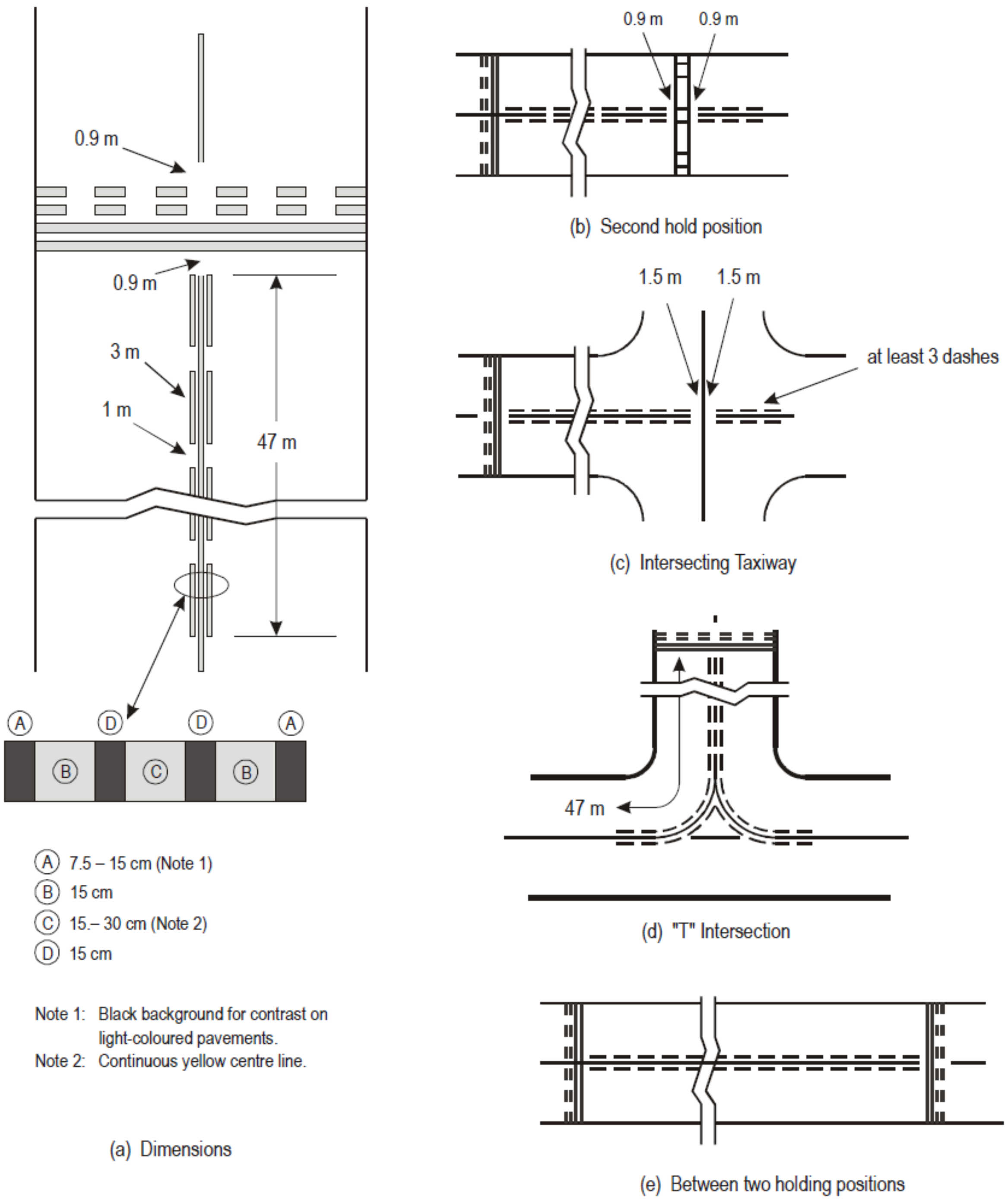


Figure C.1: Basic Taxiway markings (ICAO, 2018a). *(shown with basic runway markings)*



Ⓐ 7.5 – 15 cm (Note 1)
Ⓑ 15 cm
Ⓒ 15.– 30 cm (Note 2)
Ⓓ 15 cm

Note 1: Black background for contrast on light-coloured pavements.
Note 2: Continuous yellow centre line.

(a) Dimensions

(b) Second hold position

(c) Intersecting Taxiway

(d) "T" Intersection

(e) Between two holding positions

Figure C.2: Enhanced Taxiway center line markings (ICAO, 2018a)

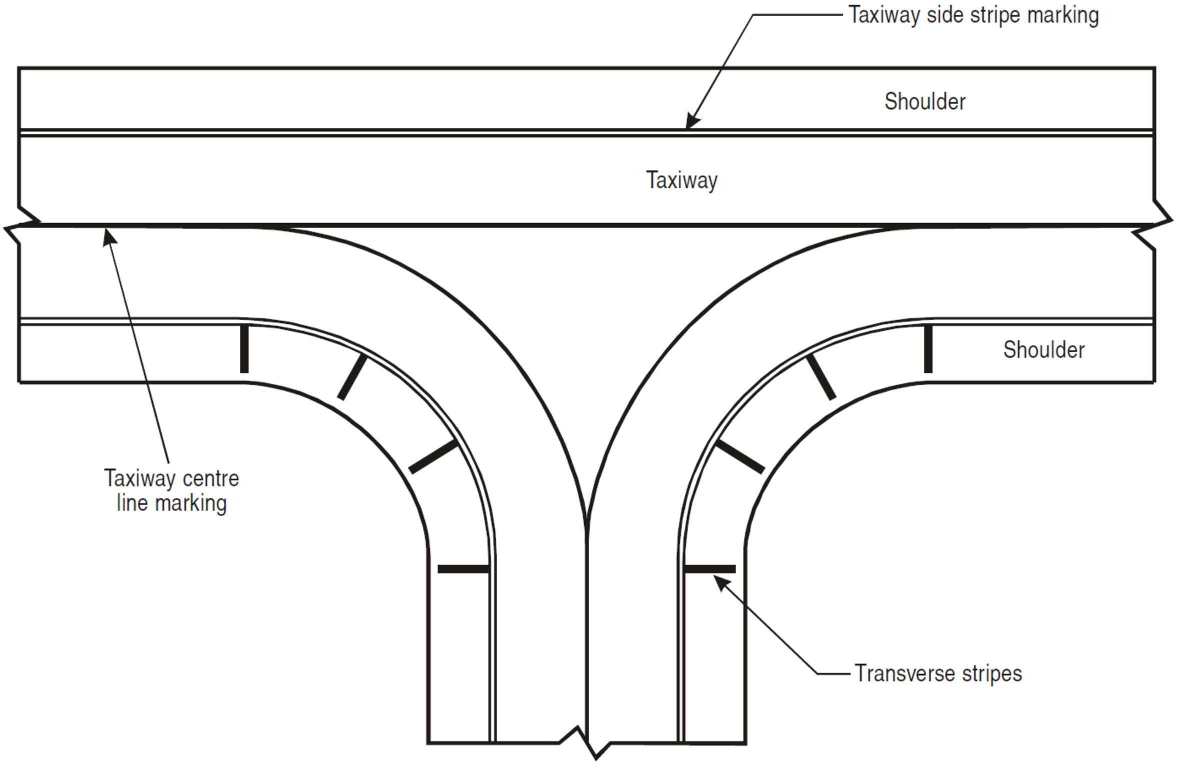


Figure C.3: Paved taxiway shoulder markings (ICAO, 2004)

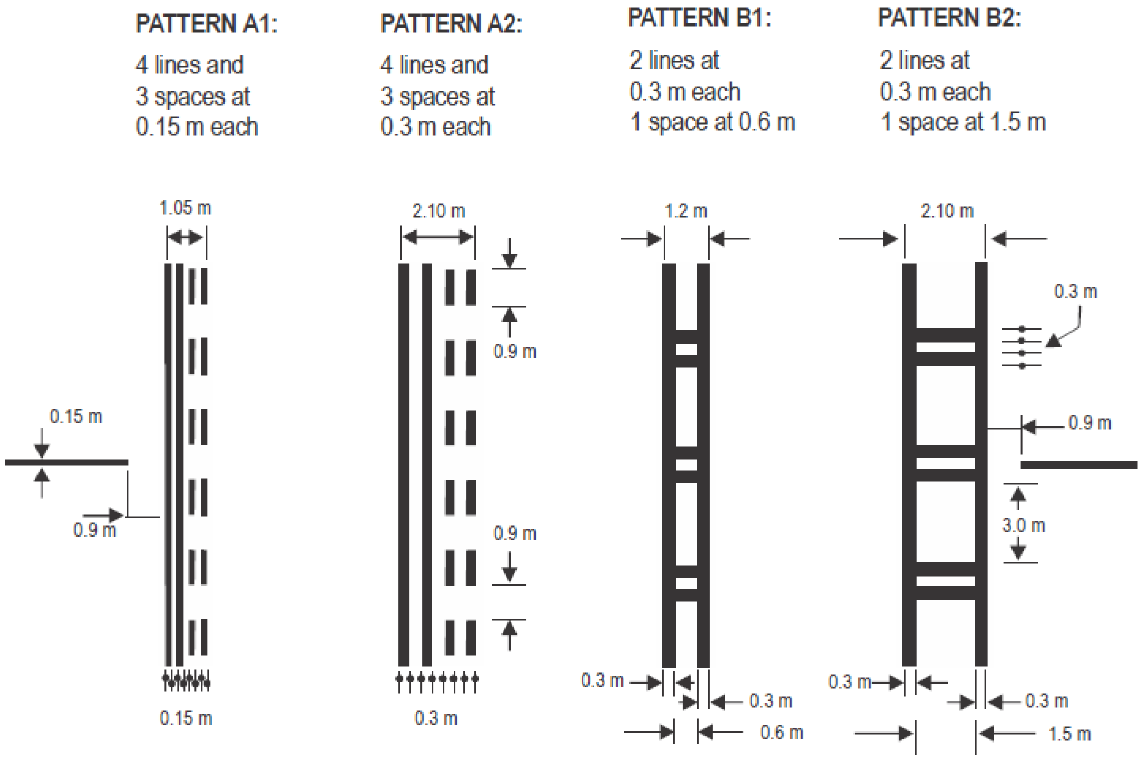


Figure C.4: Runway-holding position markings (ICAO, 2018a). *(Note: Patterns A1 and B1 are no longer valid after 2026.)*

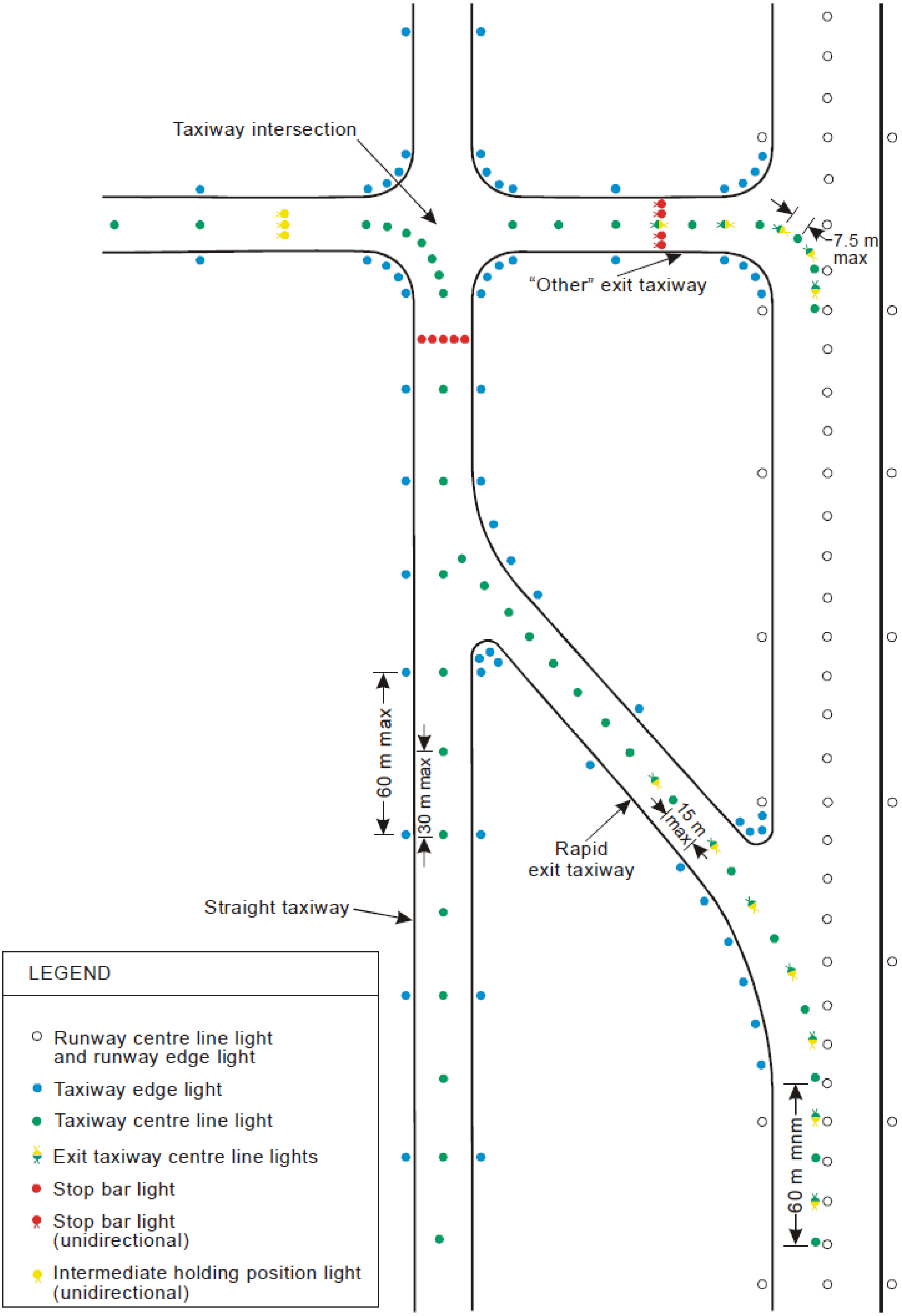


Figure C.5: Taxiway Lighting (ICAO, 2018a)

Runway designation of a runway extremity (Example)	25	Indicates a runway-holding position at a runway extremity
Runway designation of both extremities of a runway (Example)	25-07	Indicates a runway-holding position located at taxiway/runway intersection other than runway extremity
Category I hold position (Example)	25 CAT I	Indicates a category I runway-holding position at the threshold of runway 25
Category II hold position (Example)	25 CAT II	Indicates a category II runway-holding position at the threshold of runway 25
Category III hold position (Example)	25 CAT III	Indicates a category III runway-holding position at the threshold of runway 25
Category II and III hold position (Example)	25 CAT II/III	Indicates a joint category II and III runway-holding position at the threshold of runway 25
Category I, II and III hold position (Example)	25 CAT I/II/III	Indicates a joint category I, II and III runway-holding position at the threshold of runway 25
NO ENTRY	⊖	Indicates that entry to an area is prohibited
Runway-holding position (Example)	B2	Indicates a runway-holding position (in accordance with 3.12.3)

Figure C.6: Mandatory instruction signs (ICAO, 2018a)

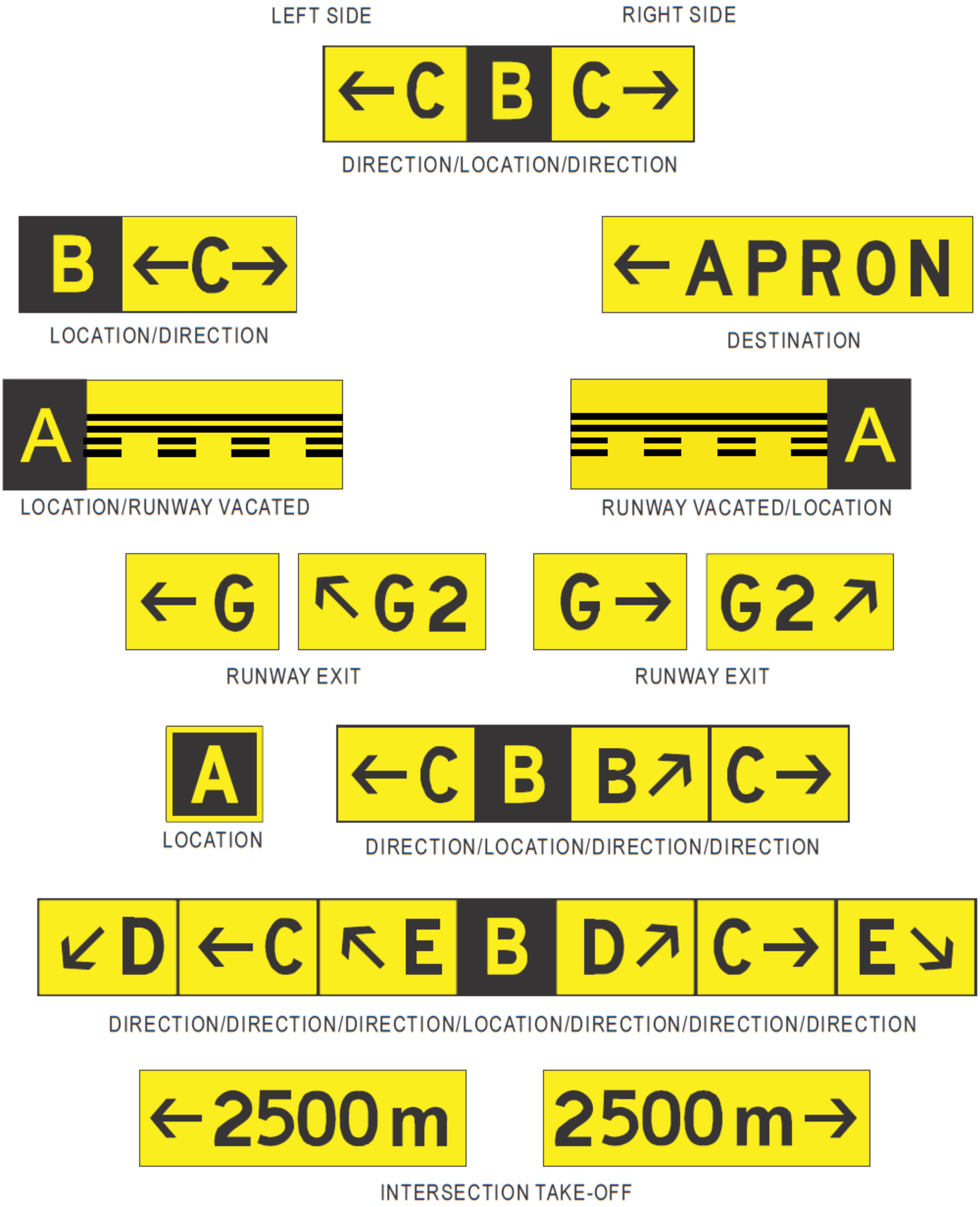


Figure C.7: Information signs (ICAO, 2018a)

D ACCIDENT/INCIDENT DEFINITIONS

Definitions from ICAO's Annex 13 (ICAO, 2016, p. 1-1 and 1-2):

Accident: An occurrence associated with the operation of an aircraft which, in the case of a manned aircraft, takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, or in the case of an unmanned aircraft, takes place between the time the aircraft is ready to move with the purpose of flight until such time as it comes to rest at the end of the flight and the primary propulsion system is shut down, in which:

a) a person is fatally or seriously injured as a result of:
  - being in the aircraft, or
  - direct contact with any part of the aircraft, including parts which have become detached from the aircraft, or
  - direct exposure to jet blast,

  except for when the injuries are from natural causes, self-inflicted or inflicted by other persons, or when the injuries are to stowaways hiding outside the areas normally available to the passengers or crew; or

b) the aircraft sustains damage or structural failure which:
  - adversely affects the structural strength, performance or flight characteristics of the aircraft, and
  - would normally require major repair or replacement of the affected components,

  except for engine failure or damage, when the damage is limited to a single engine (including its cowlings or accessories), to propellers, wing tips, antennas, probes, vanes, tires, brakes, wheels, fairings, panels, landing gear doors, windscreens, the aircraft skin (such as small dents or puncture holes), or for minor damages to main rotor blades, tail rotor blades, landing gear, and those resulting from hail or bird strike (including holes in the radome); or

c) the aircraft is missing or is completely inaccessible.

Note 1. - For statistical uniformity only, an injury resulting in death within thirty days of the date of the accident is classified, by International Civil Aviation Organization (ICAO) as a fatal injury.

Note 2. - An aircraft is considered to be missing when the official search has been terminated and the wreckage has not been located.

Incident: An occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation.

E

AAS TOWING ROUTES

Amsterdam Airport Schiphol
Sleepoverzicht

Legenda

········	GRENS LUCHTHAVENGEBIED
········	GRENS AIRSIDE (BEDRIJVENTERREIN SCHIPHOL-OOST)
········	GRENS BEDRIJVENTERREIN SCHIPHOL-OOST
········	WERKINGSGEBIED CBP - S / CPAAS
········	SECURITY GRENS SCHIPHOL-OOST
—	SLEEPROUTES
◀▭▶	ROUTE SLEEPVOERTUIGEN ZONDER VLIEGTUIG
◀▭▶	ROUTE SLEEPVOERTUIGEN ≤ 3,7 METER ZONDER VLIEGTUIG
○	SLEEPBAANKRUISINGEN BEVEILIGD MET STOPBARS
70 13	PERIFERIEHEK / HEKNUMMER
●	DOORLAATPOST
●	OMKOPPELPOST
●	PERSONEN- EN VOERTUIGENDOORLAATPOST
NS 9	NOODUITGANG NS-TUNNEL

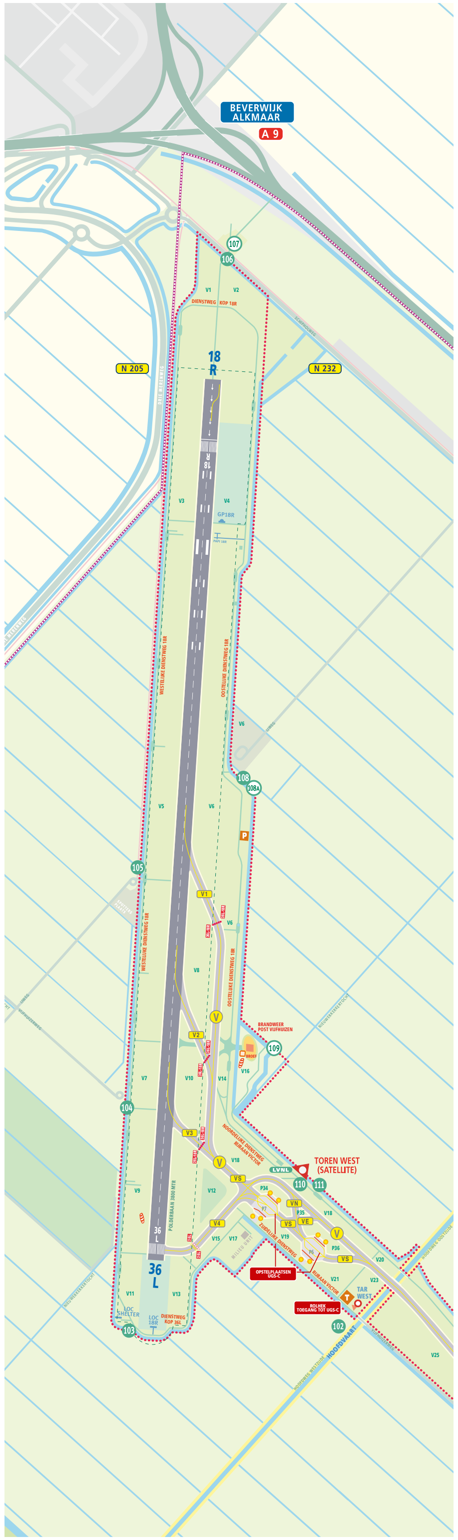
1 = KM 12.022
2 = KM 12.422 (VOEDINGSPUNT)
3 = KM 12.822
4 = KM 14.000
5 = KM 14.400 KM 14.500
6 = KM 14.860
7 = KM 15.140
8 = KM 15.400 (VOEDINGSPUNT)
9 = KM 15.775
10 = KM 16.000 (HEK 72B)
11 = KM 16.500 (HEK 72A), BIJ GEMAAL ZUID LANDZIJDE

R-NET ·B·	NOODUITGANG R-NET TUNNEL
OPSTELPLAATS UGS - A	UITGANGSSTELLING SCHIPHOL
A2	BAANSTATION
P10	REMOTE DE-ICING SPOTS (WINTER)
⬚	GRENS SENSITIVE AREA TIJDENS BZO
G G7	RIJBAANNUMMER
04-22	RUNWAY HOLDING POSITION
29	MAX. SPANWIJDTE
R44	VELDNUMMER
●●○●●	STOPBAR PERMANENT BRANDEND
●○●○●	STOPBAR SCHAKELBAAR
○●●●○	STOPBAR NIET SCHAKELBAAR, BAANGEBONDEN
○○○○○	STOPBAR BZO SCHAKELBAAR
●●●●●	STOPBAR BZO NIET SCHAKELBAAR
	WINDZAK
	LICHTMAST
D3 ●	VERZAMELPLAATS
P	PROEFDRAAIPLAATS
⇸	VERPLICHT MELDPUNT

Schiphol

F | AAS GROUND MAPS

Amsterdam Airport Schiphol Basiskaart



Schiphol

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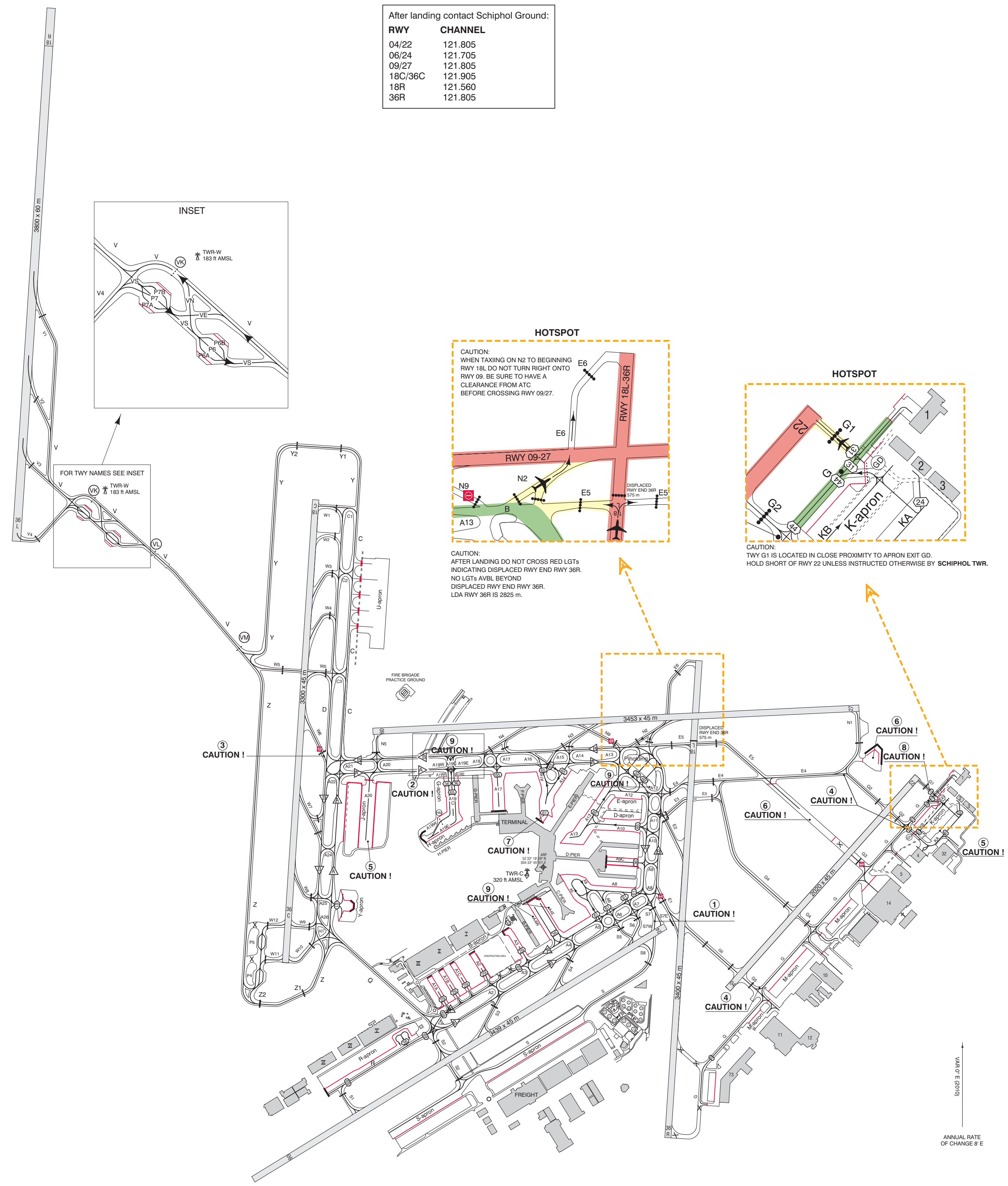
AD ELEV -11

After landing contact Schiphol Ground:

RWY	CHANNEL
04/22	121.805
06/24	121.705
09/27	121.805
18C/36C	121.905
18R	121.560
36R	121.805



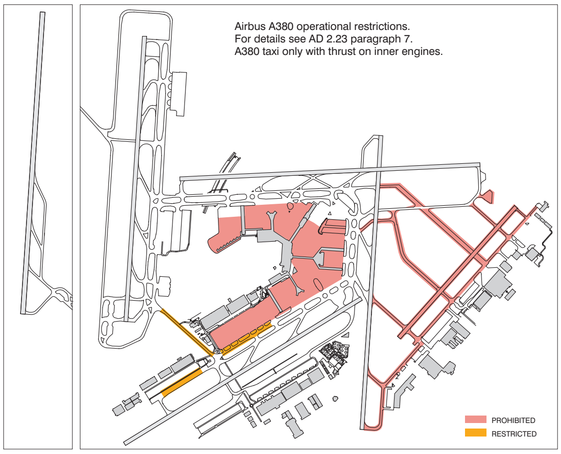
HOTSPOT

CAUTION:
WHEN TAXIING ON N2 TO BEGINNING RWY 18L DO NOT TURN RIGHT ONTO RWY 09. BE SURE TO HAVE A CLEARANCE FROM ATC BEFORE CROSSING RWY 09/27.

CAUTION:
AFTER LANDING DO NOT CROSS RED LGTs INDICATING DISPLACED RWY END RWY 36R.
NO LGTs AVBL BEYOND DISPLACED RWY END RWY 36R.
LDA RWY 36R IS 2825 m.

HOTSPOT

CAUTION:
TWY G1 IS LOCATED IN CLOSE PROXIMITY TO APRON EXIT GD.
HOLD SHORT OF RWY 22 UNLESS INSTRUCTED OTHERWISE BY **SCHIPHOL TWR.**



Airbus A380 operational restrictions.
For details see AD 2.23 paragraph 7.
A380 taxi only with thrust on inner engines.

DIRECTIONS ARE MAGNETIC
ELEVATIONS IN FEET AMSL
DIMENSION IN METERS

SCALE 1 : 20 000

m 500 0 500
ft 1000 0 1000 2000

CAUTION:

① TWY S7W designated for crossing RWY 06/24 only.

② Avoid holding on the upslope between A19 and A20 to prevent backward movement of the aircraft.

③ RTF instruction inbound 'VIA NORTH': taxi via TWY A and Northside of airport.
RTF instruction outbound 'VIA NORTH': taxi via TWY B and Northside of airport.
RTF instruction inbound 'VIA SOUTH': taxi via TWY Q.
RTF instruction outbound 'VIA SOUTH': taxi via TWY A and Q.

④ Oversteering required for aircraft with wingspan >= 36 m.

⑤ J-apron and K-apron is not controlled by ATC.

⑥ Towing only.

⑦ MAX wingspan 61 m only applicable to aircraft taxiing to E3.

⑧ Vacating RWY 04 via TWY G1 is restricted to aircraft with a maximum wingspan of 31 m due to wingspan restriction on adjacent taxiways.

⑨ Standard taxi routing, unless otherwise instructed by ATC, for ACFT docking at ACFT stands specified below:
ACFT stands B13 - B35: TWY A4W.
ACFT stands C4 - C14: TWY A4E.
ACFT stand E24: aircraft with wingspan greater than 65m: TWY A12.
ACFT stands G3 - G9 and H1 - H7, aircraft with wingspan 36m or less: from TWY A/B via TWY A19E (orange line).
ACFT stands G71 - G79, aircraft with wingspan 36m or less: from TWY A/B via TWY A19W (blue line).
ACFT stands G3 - G9 and G73 - G79, aircraft with wingspan greater than 36m: frome TWY A/B via TWY A19C.

LEGEND

⊖	No-entry: runway entry prohibited at this point. TWY E1 from TWY A and B. TWY G3 from TWY G. TWY N9 from TWY A and B. TWY W6 from TWY A, B and D.
••••••••••	STOP BAR
···(VM)	INTERMEDIATE HOLDING POSITION LIGHTED
⟨29⟩	MAX WINGSPAN 29 m LIMITED ENTRY
◁B ←	STANDARD TAXI ROUTING, UNLESS OTHERWISE INSTRUCTED BY ATC. ALL OTHER ROUTES MAY BE USED TWO-WAY ON ATC DISCRETION ONLY.
—	ATC SERVICE BDRY
12	HANGAR NO. 12
III	FREIGHT STATION NO. III
- - - -	SERVICE ROAD
X	NOT IN USE

HOTSPOT

🟥	RUNWAY
🟨	ENTRY / EXIT
🟩	TAXIWAY

CHANGE: S-apron and M-apron extended; editorial.

G STOCHASTIC MODEL

Indices:

n = index for node $n \in N$
r = index for runway $r \in R$
X = index for exit $x \in X$
Y = index for entry $y \in Y$
g = index for gate $g \in G$
c = index for runway 18C/36C scenario $c \in C$
c = index for runway 18C/36C scenario $c \in C$

Parameters:

M_a^n = total number of arriving movements over node n
M_d^n = total number of departing movements over node n
M_t^n = total number of movements over node n
A_r = number of flights arriving at runway r
D_r = number of flights departing from runway r
X_r = set of exits for runway r
Y_r = set of entries for runway r
$E_{r,x}$ = set of shares usage exit x when using runway r
$E_{r,y}$ = set of shares usage entry y when using runway r
F_g = share of flights using gate g
S_c = share of flights operating under scenario c

$$u^n_{r,x,g,c} = \begin{cases} 1 & \text{if node } n \text{ is used for the route between exit } X_r \text{ and gate } g \text{ in scenario } c \\ 0 & \text{otherwise} \end{cases}$$

$$u^n_{r,y,g,c} = \begin{cases} 1 & \text{if node } n \text{ is used for the route between gate } g \text{ and entry } Y_r \text{ in scenario } c \\ 0 & \text{otherwise} \end{cases}$$

Formula:

$$M_a^n = \sum_{r \in R} \sum_{x \in X} \sum_{g \in G} \sum_{c \in C} A_r \cdot E_{r,x} \cdot F_g \cdot S_c \cdot u^n_{r,x,g,c} \tag{G.1}$$

$$M_d^n = \sum_{r \in R} \sum_{y \in Y} \sum_{g \in G} \sum_{c \in C} D_r \cdot E_{r,y} \cdot F_g \cdot S_c \cdot u^n_{r,y,g,c} \tag{G.2}$$

$$M_t^n = M_a^n + M_d^n \tag{G.3}$$

Sets/data:

$$N = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ 125 \\ 126 \\ E1N \\ E3 \\ E4 \\ E5 \\ G2 \\ G5 \\ N2W \\ R \\ S7W \\ S2 \\ W5 \end{bmatrix}, R = \begin{bmatrix} 06 \\ 09 \\ 18C \\ 18L \\ 18R \\ 22 \\ 24 \\ 27 \\ 36C \\ 36L \\ 36R \end{bmatrix}, G = \begin{bmatrix} A \\ B \\ BC \\ CD \\ D \\ DE \\ EF \\ FG \\ G \\ H \\ R \\ S \end{bmatrix}, C = \begin{bmatrix} \text{1: Runway 18C used for takeoffs / 36C used for landings} \\ \text{2: Runway 18C used for landings / 36C used for takeoffs} \\ \text{3: Runway 18C/36C inactive} \end{bmatrix}$$

$$X_{r,x} = \begin{bmatrix} S3 & S4 & S6 \\ N9 & N1 & - \\ W6 & W7 & W8 \\ - & - & - \\ V1 & V2 & V3 \\ G4 & G5 & - \\ S2 & S1 & - \\ N2 & N3 & N4 \\ W5 & W4 & W3 \\ - & - & - \\ E1 & E2 & E5 \end{bmatrix}, Y_{r,y} = \begin{bmatrix} S1 & - & - \\ N5 & N4 & - \\ W1 & W2 & W3 \\ E6 & E5 & E4 \\ - & - & - \\ G1 & - & - \\ S7 & S6 & S5 \\ N1 & - & - \\ W10 & W9 & W8 \\ V4 & V3 & - \\ - & - & - \end{bmatrix}, A_r = \begin{bmatrix} 55{,}415 \\ 42 \\ 41{,}599 \\ 0 \\ 79{,}642 \\ 2{,}847 \\ 560 \\ 24{,}911 \\ 12{,}090 \\ 0 \\ 31{,}574 \end{bmatrix}, D_r = \begin{bmatrix} 350 \\ 14{,}292 \\ 1{,}107 \\ 53{,}104 \\ 0 \\ 2 \\ 85{,}181 \\ 691 \\ 29{,}697 \\ 64{,}262 \\ 0 \end{bmatrix}$$

$$E_{r,x} = \begin{bmatrix} 30\% & 60\% & 10\% \\ 60\% & 40\% & - \\ 30\% & 60\% & 10\% \\ - & - & - \\ 30\% & 40\% & 30\% \\ 5\% & 95\% & - \\ 50\% & 50\% & - \\ 30\% & 40\% & 30\% \\ 30\% & 40\% & 30\% \\ - & - & - \\ 30\% & 60\% & 10\% \end{bmatrix}, E_{r,y} = \begin{bmatrix} 100\% & - & - \\ 90\% & 10\% & - \\ 60\% & 30\% & 10\% \\ 60\% & 30\% & 10\% \\ - & - & - \\ 100\% & - & - \\ 40\% & 30\% & 30\% \\ 100\% & - & - \\ 45\% & 45\% & 10\% \\ 80\% & 20\% & - \\ - & - & - \end{bmatrix}, F_g = \begin{bmatrix} 13.6\% \\ 9.0\% \\ 16.1\% \\ 16.8\% \\ 7.5\% \\ 12.3\% \\ 4.1\% \\ 5.1\% \\ 3.0\% \\ 8.9\% \\ 1.3\% \\ 2.4\% \end{bmatrix}, S_c = \begin{bmatrix} 20\% \\ 20\% \\ 60\% \end{bmatrix}$$

$$\text{Example of } u^{n}_{r,y,g,c}\text{: } u^{43}_{r,y,D,1} = \begin{bmatrix} 1 & - & - \\ 0 & 0 & - \\ 1 & 1 & 1 \\ 0 & 0 & 0 \\ - & - & - \\ 0 & - & - \\ 1 & 1 & 1 \\ 0 & - & - \\ 1 & 1 & 1 \\ 1 & 1 & - \\ - & - & - \end{bmatrix}$$

Hence, node 43 is used on the route between gates D and both entries of runway 36L in scenario 1.

Assumptions:

- Routes are defined via nodes, links are not considered. Yet, all nodes are only connected by a single link. For this research nodes were selected for defining routes, since from a safety perspective nodes are more critical than links;
- As mentioned in Chapter 6, nodes are labeled by the author. Taxiway/taxiway nodes are labeled by integers: $\begin{bmatrix}1 & 2 & 3 & \ldots & 126\end{bmatrix}$, and taxiway/runway nodes are labeled by their name (see set N). Figure G.1 shows an overview of AAS with the labeled nodes. Below, detailed maps are provided with node labels (Figure G.2 - Figure G.5);

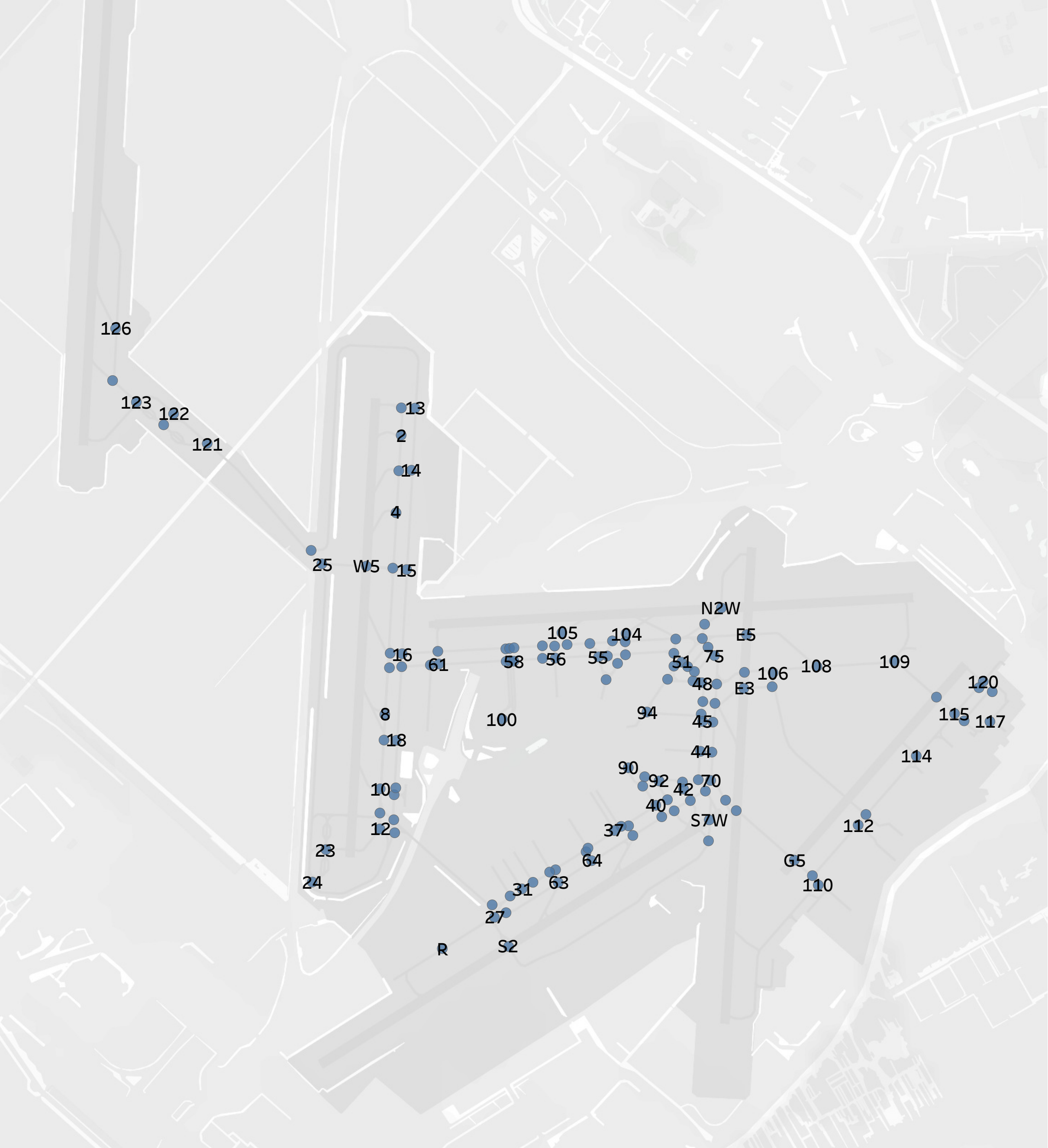


Figure G.1: Overview of labeled nodes

- Only 'handelsverkeer' (see Chapter 1) is taken into account: commercial air traffic (both passenger and freight), and does not include general aviation and technical air traffic;
- Only taxiing movements are taken into account, no towing traffic;

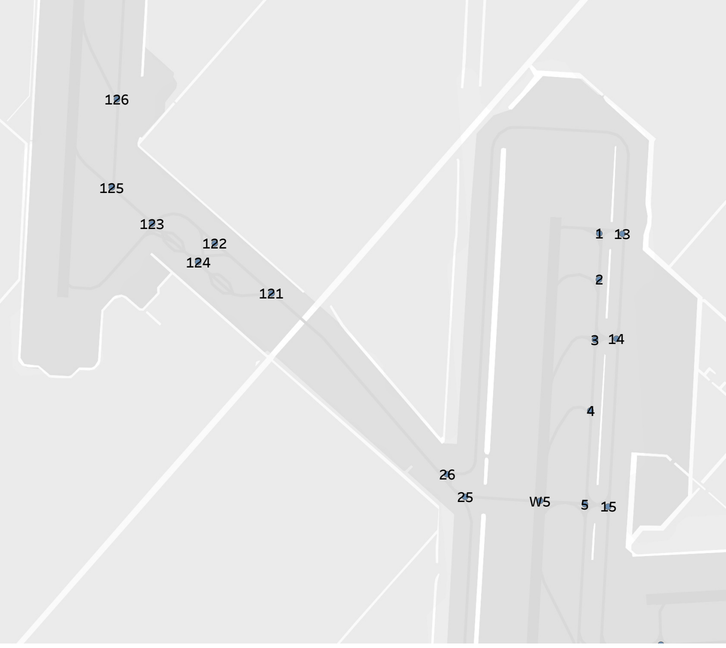


Figure G.2: Detailed overview of node labels 1

- Number of flights using a certain runway for arrival or departure are based on 'year of use' (*gebruiksjaar*) 2018 (November 2017 - October 2018) (BAS, 2018) - this is the first year of which data is available for 'handelsverkeer' specific;
- In year of use 2018 no significant maintenance was executed on runway 06/24 and/or runway 18L/36R, which are the preferred runways (BAS, 2019a);
- Share of flights using a certain set of gates are based on aggregated data between January 2016 and October 2017 - this data was available within NACO;
- The gates are aggregated to bays as shown in Figure G.6. Also stand with direct access to taxiway Alpha are aggregated. The split of these gates to bays are based on odd/even gate numbers, syncing with the rest of gates of the pier to the bay;
- No distinction is made in shares of gate usage per runway;
- Three scenarios are defined (see the set C). The scenarios influence the routes to/from the polderbaan (runway 18L/36R):
  - *Runway 18C used for takeoffs / 36C used for landings:*

    Taxi routes to/from runway 18L/36R via taxiway Zulu
  - *Runway 18C used for landings / 36C used for takeoffs:*

    Taxi routes to/from runway 18L/36R via taxiway Yankee
  - *Runway 18C/36C inactive:*

    Taxi routes to/from runway 18L/36R via taxiway Wiskey 5 (crossing runway 18C/36C)

  For taxi routes other than to/from runway 18L/36R, routes are identical for all scenarios;
- Routes are defined based on observations (commonly used) with taking defined taxiing directions into consideration;
- Besides, runway configurations as defined in Section 5.3 are taken into consideration for defining routes (e.g. departures of runway 09 are according to the preferred runway configurations combined with landings on runway 36R. Therefore, departing routes towards runway 09 are not directed via taxiway Quebec).

Figure G.3: Detailed overview of node labels 2

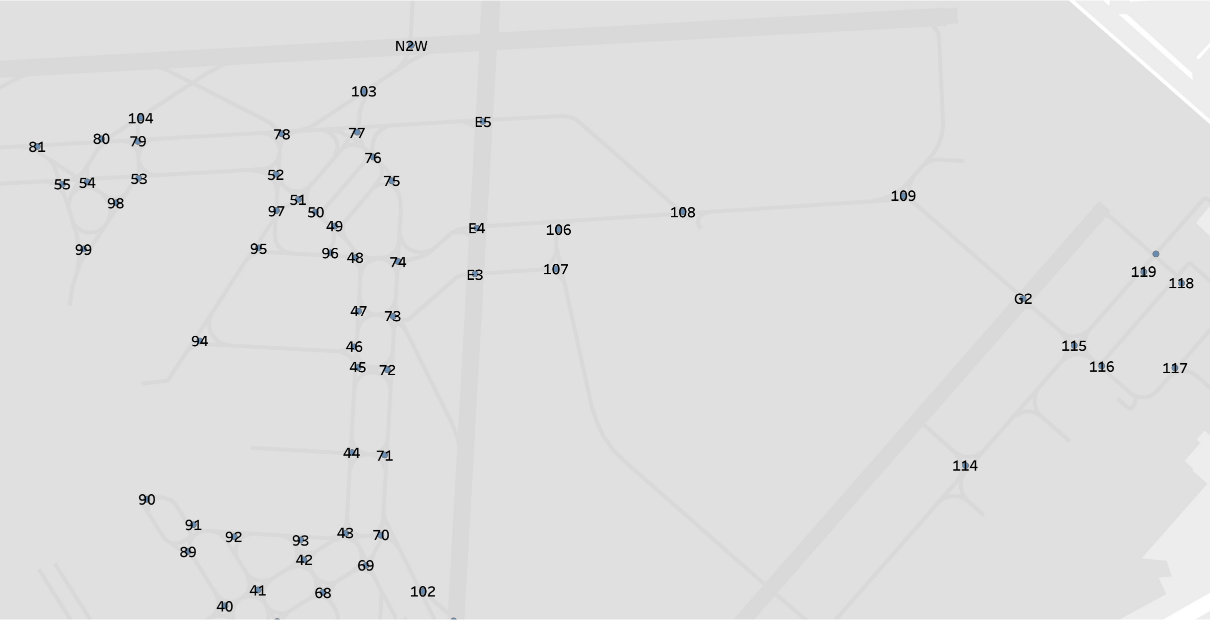


Figure G.4: Detailed overview of node labels 3

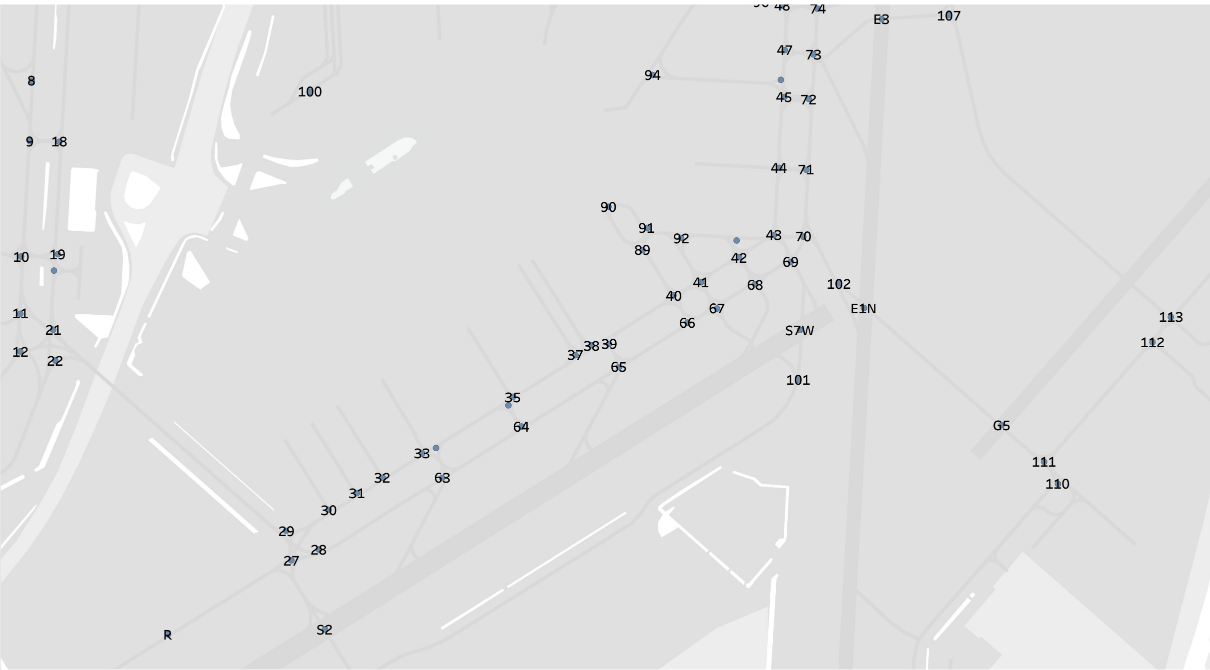


Figure G.5: Detailed overview of node labels 4

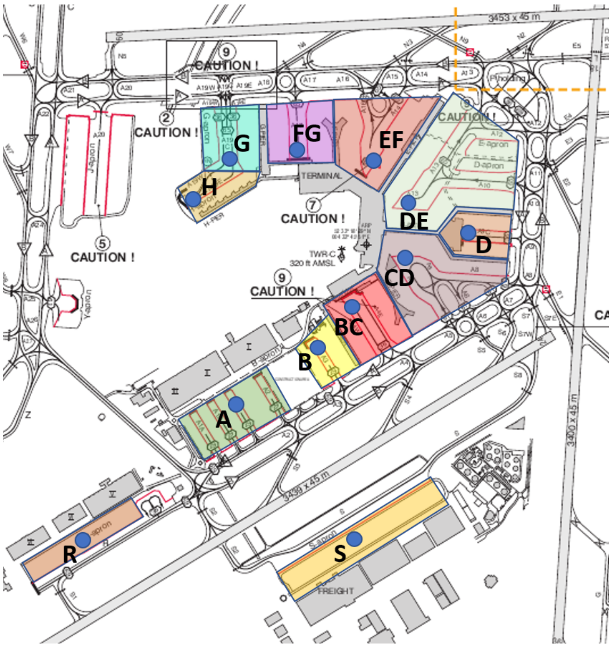


Figure G.6: Overview of gate areas aggregated to bay nodes. The figure also shows the location of the bay nodes.

H

DETAILED HEAT MAPS

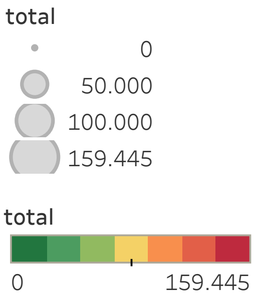


Figure H.1: Legend of the heat map

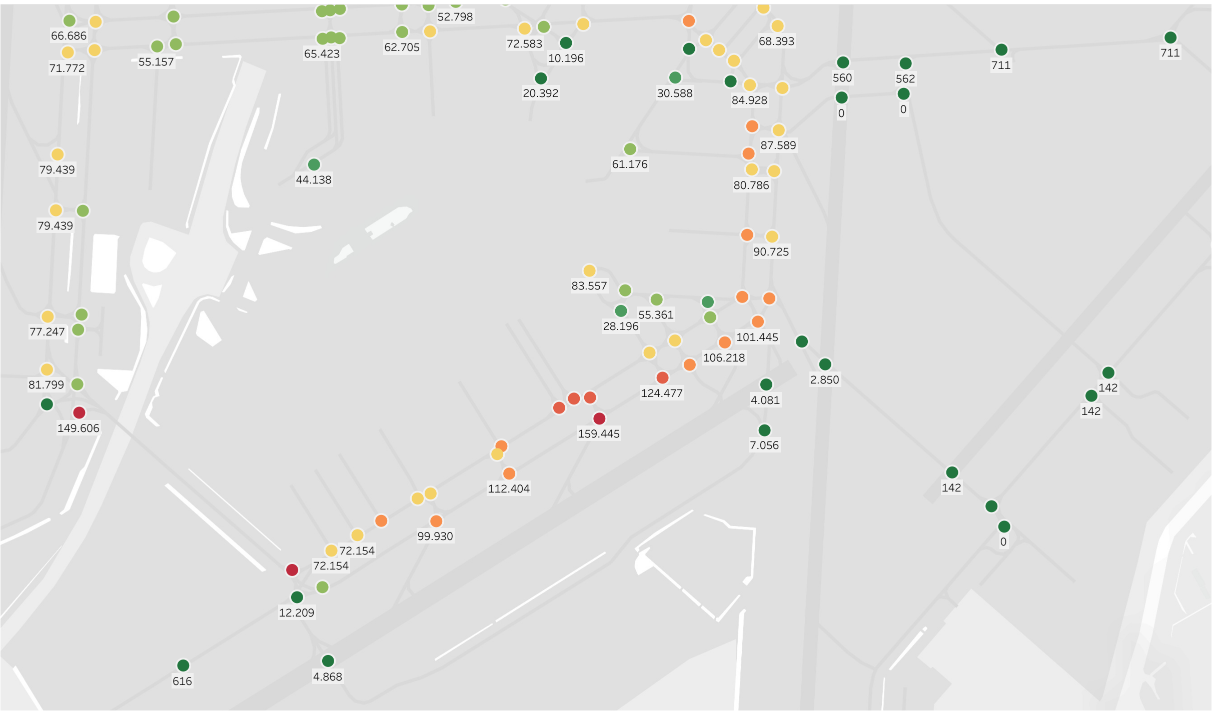


Figure H.2: Heat map detail 1

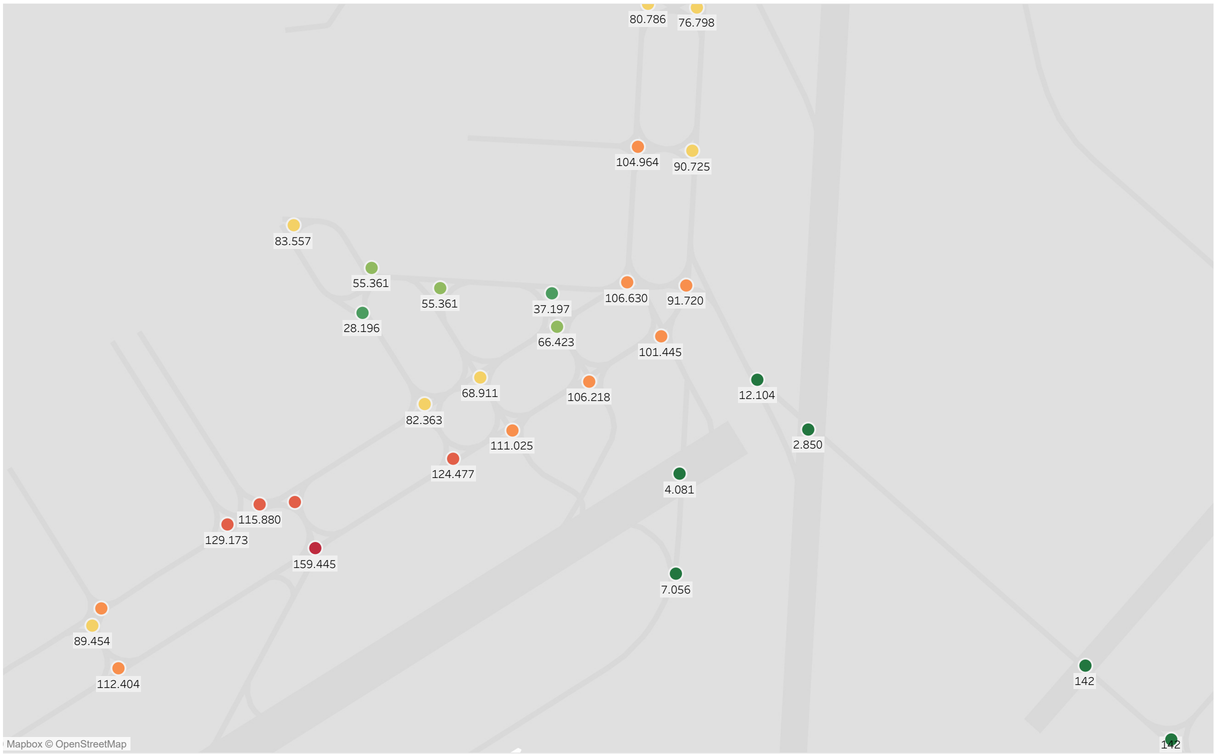


Figure H.3: Heat map detail 2

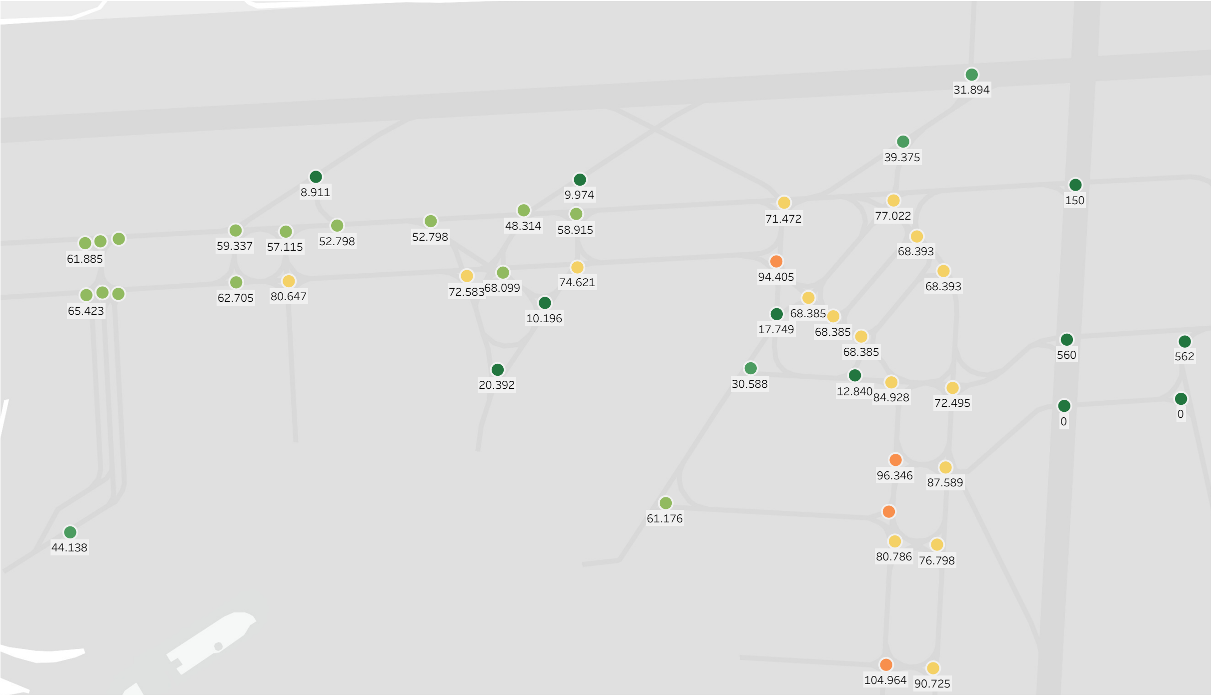


Figure H.4: Heat map detail 3

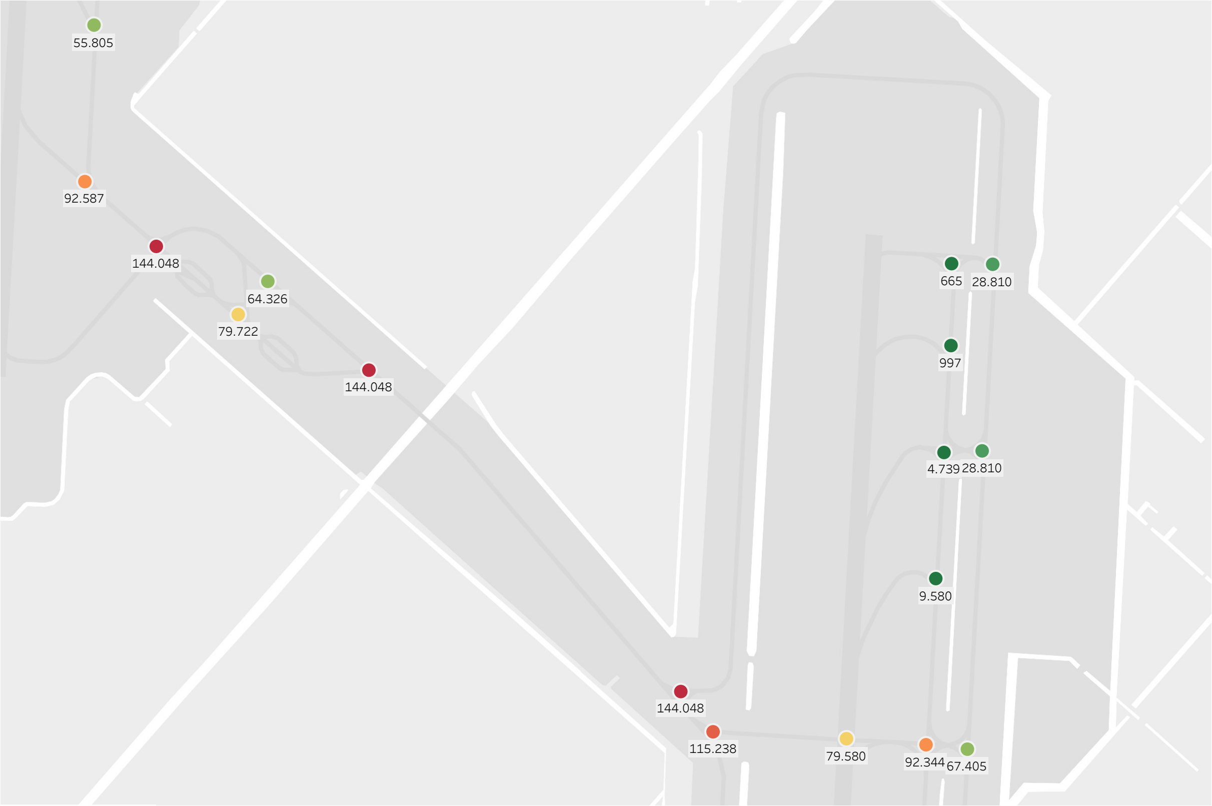


Figure H.5: Heat map detail 4

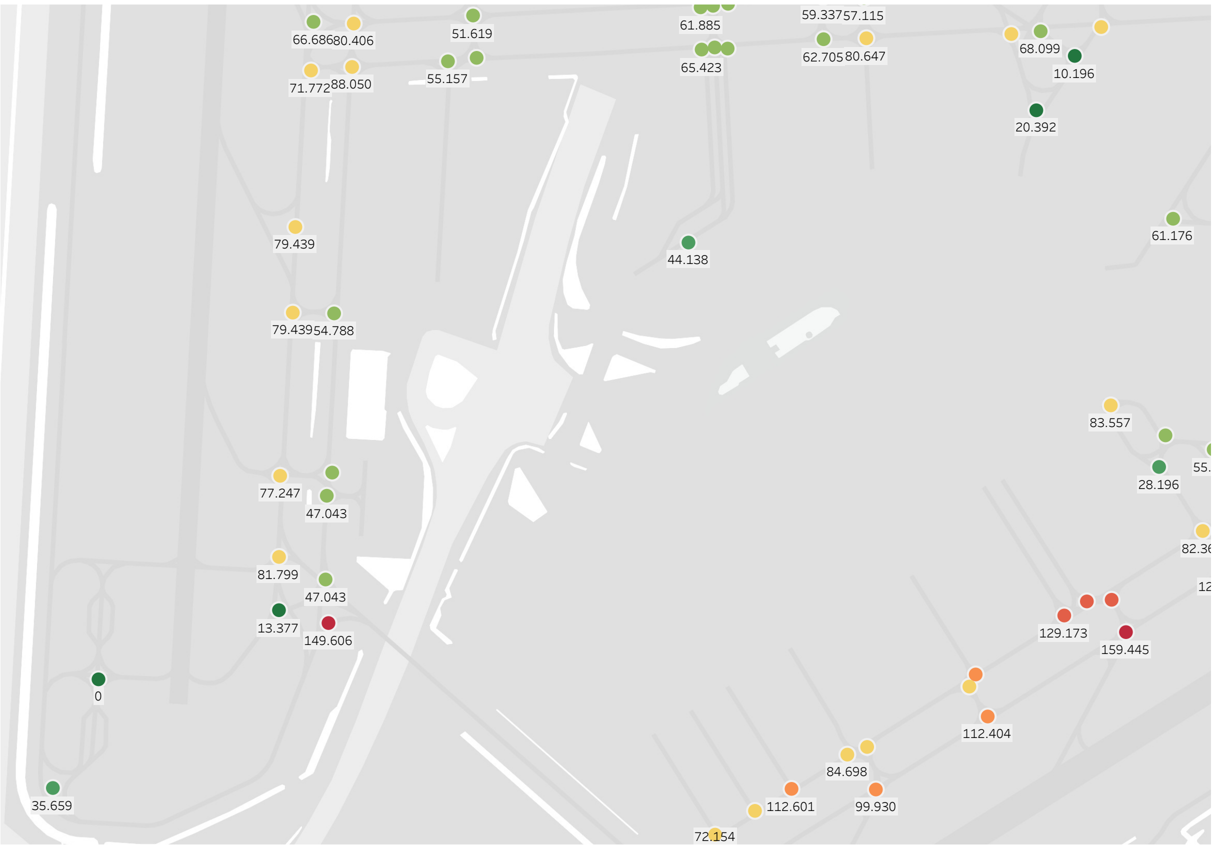


Figure H.6: Heat map detail 5

I INTERVIEW TRANSCRIPTS

Transcripts of the interviews can be obtained in a separate booklet through a request to the author of this thesis.