MSc Thesis in Engineering and Policy Analysis

An Autonomous Drone Approach to Runway Condition Reporting

A Case Study for Airside Innovation at Schiphol Airport

Isaac Hall
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I.R Hall

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I.R Hall(2025)
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Faculty of Technology, Policy and Management
Delft University of Technology

Graduation Committee:	Prof.dr.ir. P.H.A.J.M van Gelder	TU Delft
	Prof. dr. M.E. Warnier	TU Delft
	Ir. R. Kamerling	Royal Schiphol Group

Executive Summary

Schiphol Airport aims to achieve fully autonomous airside operations by 2050, driven by the ambition to reduce human presence in high-risk environments and enhance operational efficiency. Drones present a promising airside innovation within this vision, offering autonomous inspection capabilities and adaptability to dynamic environments. This ambition is reinforced by developments at the national level, where the Dutch Minstry of Infrastructure and Water Management (IenW) actively promotes the integration of drones into the airspace ecosystem. Schiphol's involvement in the Dutch Drone Delta innovation consortium reflects its growing commitment to exploring drone use cases in operationally challenging environments.

To explore the integration of autonomous drones at Schiphol Airport, Runway Condition Reporting (RCR) is identified as a suitable case study—due to its repetitive and linear nature with a critical function in airside safety. RCR involves the collection of runway surface condition data using a MARWIS sensor system, which provides pilots with up-to-date condition reports prior to take-off and landing. Currently, this task is carried out manually by airside vehicles, known as *Kievits*, that traverse each runway multiple times a day as they open and close. This autonomous drone approach to RCR, involves a flight trajectory between two dedicated hubs which would be positioned at either end of the Polderbaan runway. This use case provides a lens through which the challenges of autonomous drone integration at Schiphol can be explored.

This research explored autonomous drone RCR at Schiphol Airport according to three dimensions: *reliability*, *effectiveness*, and *safety*. Within these dimensions, the study aimed to assess whether and to what extent, drone systems can be utilized for an operational runway inspection task within the constraints of the airside environment. This led to the following main research question.

"How can drones be utilized reliably, effectively and safely within Schiphol Airport's operational environment to automate runway condition reporting?"

To answer this question, the research followed a staged case study structure—where each analysis builds upon the previous and is iteratively validated through stakeholder insights. The study began with an analysis of the technical feasibility of reliable drone flight at Schiphol, establishing system requirements and constraints. This was followed by the design of an optimised flight trajectory and accompanying operational protocol, aimed at producing an effective RCR concept in the airside context. As the final stage, a safety risk assessment was conducted using a Hazard and Operability Analysis (HAZOP) analysis, in collaboration with key internal and external stakeholders, to evaluate the operational risks of the developed concept. To support communication and deepen system understanding, the research included the development of a visualisation model that integrated case study findings with operational Schiphol data.

To assess reliability, the study evaluated commercially available drone platforms against Schiphol-specific criteria including performance requirements and weather conditions. Using weighted decision making, *validated through four expert interviews*, the DJI Matrice 350RTK (M350RTK) was selected as the suitable drone system. Analysis of historical weather data revealed that the drone could, in most cases, perform reliably— but wind gusts exceeding 12m/s, common during afternoon operations, would limit annual operability to approximately 64%. This identifies wind resistance as a critical constraint within the reliability dimension of autonomous drone RCR, indicating a need for higher performance thresholds.

To assess effectiveness, a flight trajectory and operational protocol were developed for the Polderbaan. Using Operations Research (OR) problem framing, a constrained flight path was optimised that, on paper, could perform RCR in *3 minutes and 41 seconds.* The protocol includes geofenced corridors with tailored emergency procedures, Return-to-Home (RTH) and Emergency Landing (EL). Together, the trajectory and protocol formed the basis for the operational concept evaluated in the subsequent

risk assessment. To support stakeholder communication, the concept was visualized using Agent-based Modelling (ABM). By integrating the developed RCR use case with historical vehicle and aircraft movement data, system insights could be obtained. The model, simulated for one operational day, demonstrated *27 daily drone inspections* with a total operational flight time of *1 hour and 45 minutes*. Model insights cautiously hint at potential efficiency improvements compared to the current vehicle-based approach, requiring further research, but also show operational bottlenecks in current drone Controlled Traffic Region (CTR) regulation, due to simultaneously operating drones.

To assess safety, a HAZOP analysis was conducted in collaboration with key stakeholders from within Schiphol Airport and Luchtverkeersleiding Nederland (LVNL). During an official Schiphol safety meeting, attended by six key stakeholders, the flight trajectory was assessed step by step. For each phase, potential system deviations and their consequences for airside operations were discussed, focusing on the probability of occurrence within an operational year and the severity of impact. This process *identified 51 system deviations* across the drone's operational trajectory, including four with notably high-risk scores:

- **Compromised Airspace** due to wildlife.
- **Loss of Drone Control** due to GPS spoofing or signal jamming.
- **Emergency Protocol Failure** due internal system malfunctioning or signal jamming.
- **Ground Collisions** due to wind gusts.

These risks have the impact of rendering runways unusable, or in some cases result in a complete temporary halt of all airside operations—serious impactful consequences for the airside. The safety analysis identified *wind gusts, internal system malfunction, and external party interferences* as common root causes for the majority of identified system deviations, with the probabilities happening multiple times in an operational year. HAZOP findings concluded that autonomous drone integration is not yet realistic without significant preventative measures.*Stricter geofencing, system redundancies, and enhanced coordination protocols* were identified as critical preventative measures, though their impact on risk probability ratings requires further research.

Despite the serious risks associated with autonomous drone integration, this case study provides Schiphol with a baseline reference for evaluating the potential of autonomous drone innovations at airside. It presents a use case aligning with Schiphol's vision of an autonomous airside, with reduced human-airside operations, whilst also hinting at efficiency gains. The findings recommend a strategic roadmap, starting with low-risk, non-runway use cases that can build up operational experience and stakeholder involvement. By doing this, the road can be developed towards further exploration of high-criticality tasks such as RCR. Practical policy recommendations include engaging with key stakeholders to explore realistic pilot projects, improving drone system robustness, and engaging early with regulatory authorities to explore airspace arrangements. Use cases focussed on operational runways are currently not realistic, but inspections in less sensitive areas offer a viable starting point for innovation development.

This research scientifically contributes a replicable, exploratory case study framework combining various analyses, stakeholder interviews, and structured risk assessment. It demonstrates the value of early-stage risk identification in complex operational settings, where live testing is not feasible. Future research should prioritize the validation of risk mitigation strategies, drone protocol development in coordination with field operators, and simulation model extensions that can give insights into real-world operational complexity.

In conclusion, while this study demonstrates that autonomous drones, on paper, can perform RCR reliably when wind conditions allow and effectively under constrained conditions, the safety dimension can currently not be satisfied for implementation at Schiphol Airside. Nonetheless, this work lays the groundwork for a structured, stepwise path forward—both at Schiphol and in similar regulated domains—toward reliable, effective and safe integration of autonomous drones at airside.

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With this thesis, I bring my time in Delft to a close, and look back at an amazing period of my life. I hope this research will interest you, the reader, in the autonomous future of airports.

Isaac Hall
Delft, July 2025

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Acronyms

ABM	Agent-based Modelling	vi
APM	Airside Process Management	17
ASM	Asset Management	17
ATC	Air Traffic Control	10
CAS	Collision Avoidance System	8
CTR	Controlled Traffic Region	vi
DAC	Designated Air Corridor	8
DDD	Dutch Drone Delta Organisation	2
DDO	Day-to-Day Operations	17
EASA	European Union Aviation Safety Agency	10
EL	Emergency Landing	v
FMA	Flow Manager Aircraft	5
FOD	Foreign Object Debris	10
GRF	Global Reporting Format	5
GNC	Guidance, Navigation and Control	6
GNSS	Global Navigation Satellite System	7
GPS	Global Positioning System	7
HAZOP	Hazard and Operability Analysis	v
HREC	Human Research Ethic Committee	16
ICAO	International Civil Aviation Organization	5
IenW	Minstry of Infrastructure and Water Management	v
ILS	Instrument Landing System	11
KNMI	Koninklijk Nederlands Meteologisch Instituut	15
LVNL	Luchtverkeersleiding Nederland	vi
M350RTK	DJI Matrice 350RTK	v
OLS	Obstacle Limitation Surfaces	33
OR	Operations Research	v
RCR	Runway Condition Reporting	v
RTK	Real-time Kinematic	28
RESA	Runway End Safety Area	33
RTH	Return-to-Home	v
RWYCC	Runway Condition Code	74
WDM	Weighted Decision Matrix	15

1 Introduction

Every year, more than 61 million travellers pass through Schiphol Airport, an ever-moving complex system where safety is the priority and efficiency the objective (Royal Schiphol Group, 2025). As one of Europe's largest aviation hubs, Schiphol Airport is continuously evolving to meet international standards and the growing demands of global air travel (Airports Council International, 2023). Whilst Europe's skies become more crowded, Schiphol evolves by investing in innovation, not only through advanced terminals or efficient security, but also through a quiet transformation happening on its airside (Royal Schiphol Group, 2025, p. 9).

At the heart of this transformation lies a bold vision to make airside operations fully autonomous and emission-free by 2050 (Royal Schiphol Group, 2020b). This shift is not only seen in the Netherlands, major airports around the globe are following suit, driven by the wish to reduce human presence in high-risk areas and optimise workflows for a growing demand (Arun, 2024). Existing innovations such as autonomous air traffic coordination and airside transport highlight the autonomous shift already in motion in Amsterdam (Royal Schiphol Group, 2020a)

Autonomous drones embody the next step in Schiphol's vision, with a proven track record in offering real-time high-accuracy data collection and modular adaptability to dynamic environments, whilst also contributing to near zero-carbon logistics (Fan & Saadeghvaziri, 2019; Papadopoulos & Gonzalez, 2021). In this study, autonomous drones play a role in Schiphol's operational environment, as an approaching to RCR, a key airside inspection that assesses runway surface conditions before aircraft approach and departure. Automating RCR, a repetitive and linear runway inspection, presents an opportunity to improve operational efficiency whilst reducing airside personnel. However to succeed, this autonomous approach must coexist with dynamic airport operations complicating the integration of autonomous drones(Gomez-Beldarrain, Verma, Kim, & Bozzon, 2025). Significant automatisation hurdles have been shown to arise due to multi-stakeholder involvement and the high risk nature of airside operations (Gomez-Beldarrain, Verma, Kim, & Bozzon, 2024).

This thesis research is conducted as a graduate internship at Schiphol Airport in collaboration with Delft University of Technology. Preparatory research explored the wide-scale operational potential of autonomous drones at Schiphol Airport. This included consultation with Schiphol stakeholders and concluded with a focus on RCR, as explained later in this research. This thesis develops a case study for autonomous drones, consisting of trajectories and protocols supported by a technical feasibility analysis and assessment of operational risk. As an exploratory case study, this research is intended as a use case for future drone innovations at Schiphol Airport.

1.1 Research Problem

Whilst automation has potential to transform industries, sustained adoption within organisations often falls short of expectations, due to the discrepancy between technological and organisational readiness Gomez-Beldarrain et al. (2024). The highly standardized environment of Schiphol Airport faces difficulties in implementing automated processes, due to complex networks of stakeholders and context-specific factors (Gomez-Beldarrain et al., 2024). In this thesis, this problem is addressed by providing the organisation with a use case aligned with the operational visions of stakeholders. Aligning with safety expectations and airside operational infrastructure—a proven pitfall in autonomous advancement—ensures the challenge is met head-on (Edelman et al., 2023).

RCR is crucial for safe airside operations, currently performed manually at Schiphol by airside personnel named *Kievits*, a simple linear task, deemed ready for innovation by Schiphol stakeholders, see Appendix E.3.4. Personnel working on active runways face health and safety hazards, such as operational accidents and daily exposure to jet engine emissions, which have been shown to impact

respiratory health (Bendtsen, Bengtsen, Saber, & Vogel, 2021). Integrating autonomous drones for RCR presents an alternative to lessening direct human involvement in a high-risk area.

However, drones introduce challenges of their own. Airsides host expensive aircraft and critical infrastructure, where drone-related incidents can have heavy financial and safety consequences. This is shown in a simulation model by of Frankfurt Airport, where a 48-hour drone-caused shutdown led to €35 million in airline welfare costs (Wendt, Voltes-Dorta, & Suau-Sanchez, 2020). Even though drone performance consistency is improving, they pose a risk of high-impact collisions. This contributes to stakeholder resistance and reinforces the perception of drones as dangerous and an unreliable airspace liability (Shvetsova & Shvetsov, 2020). Recent studies at Schiphol indicate organisational factors pose major hurdles to automation adoption — including a lack of consensus among stakeholders, the need to tailor technology to the specific operational context, and unclear procedures for maintaining introduced automated systems after deployment. Such factors have made the sustained adoption of autonomous technologies at Schiphol slow and more difficult than anticipated (Gomez-Beldarrain et al., 2024, 2025). It is therefore important to research how these hurdles can be overcome, as automation is regarded as a key social-technical enabler in realizing drones as a consistent part of air traffic (Alsamhi, Ma, Ansari, & Gupta, 2019).

1.2 Societal and Public Policy Relevance

The Dutch IenW has expressed strong interest in the development of drone applications within Dutch airspace, identifying integrated operations as a necessary part of the country's future mobility ecosystem (Zondervan, de Wit, & Ouderling, 2022). As part of this ambition, IenW collaborates with the Dutch Drone Delta Organisation (DDD), an innovation consortium dedicated to exploring drone use cases in complex societal environments (Zondervan et al., 2022). As an active member of the DDD, Schiphol Airport plays a role in addressing this societal challenge. By developing a case study for RCR, a step is made in the realization of autonomous drone integration.

Autonomous drones show that they can decrease human errors in infrastructure inspections and monitoring, by offering fast and accurate detection of potential problems, often in combination with the developing field of artificial intelligence (Rodríguez, Tafur, Daza, Vidales, & Rincón, 2024). By proactively adopting autonomous inspection and monitoring technologies, Schiphol addresses the societal agenda by increasing passenger safety while minimising travel disruptions. In the global aviation sector, there is an urgency for safer airport operations as runway incidents remain a significant concern; runway excursions — when an aircraft veers off or overruns the runway — accounted for 23% of aviation accidents between 2005 and 2019 (EUROCONTROL, 2021). To minimise these occurrences, clear runway condition reporting to aircraft pilots is key, which could potential benefit from an autonomous drone approach.

Schiphol Airport, being a critical global transportation network in Europe with a societal responsibility, has the obligation to take action on the advancements to improve airport operations and general safety where possible (Royal Schiphol Group, 2025, p. 141). As a leading European airport, Schiphol's vision of autonomous technology sets a global precedent for airports. The growing demand for air travel indicates that passenger volumes will not decrease in the foreseeable future—making efficiency improvements beneficial for sustainability goals (Royal Schiphol Group, 2025, p. 21). By pioneering autonomous airside operations, Schiphol builds towards international aviation policies on automatisation and regulatory frameworks that support safe and scalable drone integration. These advancements align with broader public policy goals, such as passenger safety, infrastructure resilience, and sustainable aviation growth (Kantenbacher, Hanna, Cohen, Miller, & Scarles, 2017)

1.3 Scientific Relevance

This research contributes to the field of autonomous technologies within high-stakes and complex environments, focusing on the interplay between reliability, effectiveness and airside safety. While existing scientific literature on autonomous systems in controlled airspace and critical infrastructure is growing, research on case-specific approaches remains limited (Edelman et al., 2023). By providing a

specific use case risk assessment, complemented by a visualisation model, the study aims to contribute a case study, beneficial for future scientific developments. By collaborating with a major airport, this study provides real-world insights into the possibilities of autonomous technologies, building on literature describing the pitfalls of such an integration (Gomez-Beldarrain et al., 2024, 2025). This research builds on scientific advancements in real-time data processing and sensor-based monitoring capabilities of modern drone systems (Congress, Puppala, Treybig, Gurganus, & Halley, 2022). By developing a flight trajectory in accordance with Schiphol-specific constraints, operational data, and in-house risk identification, this study aims to lay the ground for further autonomous drone use in complex high-stakes environments. The integration of real-world Schiphol airside data provides a foundation for the study's findings, ensuring a realistic evaluation of drone-based inspection systems on paper, as well as analysing the environmental impact on the designed system (Rodríguez et al., 2024, p. 11). The findings aim not only to benefit airports but also other complex environments considering the integration of autonomous technologies.

2 State of the Art

The rapid evolution of drone technology in combination with developments seen in complex airport environments demands a *state-of-the-art review* to position this thesis within both academic research and real-world innovation.

2.1 Approach

The following chapter examines four interrelated topics:

1. *Contemporary Operational Airport Development*:
2. *Autonomous Advancements and Capabilities of Drone Systems*
3. *Safety Considerations of Drone Systems*
4. *Contemporary Drone Integration at Airports*

Academic literature is collected using search queries exploring academic databases Google Scholar and Scopus for terms including but not limited to: *"Drone Applications in High-risk Areas"*, *"Autonomous Drone Operations"*, *"Drone Infrastructure Inspections"*, *"Drone Risk Management"*, *"Airport-drone Integration"* and *"Runway Condition Reporting"*. To attain the essence of a state-of-the-art literature review, certain inclusion and exclusion criteria are taken into account: studies are published in peer-reviewed journals or are authoritative technical reports, within a preferred timescale of 10 years. Due to drone technology being a relatively new advancement, papers outside of this timescale are deemed more speculative. Studies address drone applications or risk topics, with an emphasis on airports or similarly complex systems. Exclusion criteria eliminate sources that lack methodological rigour, are unrelated to drone technology or present speculative concepts without practical validation. Alongside academic literature, trial reports for airside developments and drone use cases are retrieved from web-published sources and Schiphol's up-to-date internal documentation.

2.2 Contemporary Airside Developments

Airside operations are a principal subsystem of airports with a focus on efficiency and functionality, lending itself well to state-of-the-art developments surrounding the wider *Industry 4.0 developments*, a vision of a revolutionized future concerning digitalization, automation and sustainability (Ghobakhloo, 2019; Zaharia & Pietreanu, 2018). In recent years, growing traffic volumes and high-performance demands have intensified attention on airside efficiency, resulting in an increase in the adoption of digital and automated solutions, fed by a constant flow of innovation (Zaharia & Pietreanu, 2018). These modern initiatives seek to optimise practices across all aspects of the airside, akin to the industry 4.0 expectations of a revolutionized industry. The framing of the wider goal of contemporary airsides highlights the themes of the following state-of-the-art exploration, discussing runway inspections and drone system developments

2.2.1 Current Runway Inspection Procedures

RCR plays a role in the wider operation of a runway inspection prior to their operational use. Therefore to understand and assess the usability of an autonomous drone for RCR it is important to know its role and position in this wider operation. *The following state-of-the-art description is based on 2024 internal Schiphol procedures.*

A runway inspection happens before a runway opens, when an open runway has not been used in a twenty-minute time frame, when a runway changes from landing to departure or vice versa and after ad hoc maintenance (Royal Schiphol Group, 2024c). It is also possible that a re-assessment is required due to corrupted data or when it is deemed reasonable that the weather has changed after an assessment, for example, due to sudden rainfall or hail (Royal Schiphol Group, 2024b).

LVNL, a key stakeholder at Schiphol, requests the opening of a runway, followed by the start of execution processes by Flow Manager Aircraft (FMA) with operational services (havendienst), inspecting the requested runway using one of the manned inspection vehicles named "Kievit". Runways in continuous use, such as the Polderbaan, are inspected according to set time intervals, but can be deviated from (Royal Schiphol Group, 2024c). The designated Kievit traverses the requested runway, conducting various inspection tasks:

- *Runway Condition Reporting:* Measure friction, detect contaminants and classify surface conditions according to international reporting codes.
- *Wildlife Management:* Survey the runway strip and adjacent areas for birds and other wildlife; if necessary, perform scaring-off interventions to mitigate bird strikes.
- *Obstacle removal:* Removing obstacles preventing runway use.
- *Foreign Object Debris Removal:* Inspect the runway surface, runway end safety areas, and high-risk zones for debris; collect and dispose of all.
- *Approach and Departure lighting inspection:* Visually verify the integrity, alignment, and functionality of approach slope lights, runway edge lights, touchdown zone lights, and other visual aids.
- *Runway Lighting Inspection:* Check all runway edge, centreline, and threshold lights for proper operation and alignment; report any failures.
- *Road and Day Sign Inspections:* Ensure runway and taxiway signs are correctly positioned, clean, and visible in daylight conditions.
- *Inspecting Precision Approach Path Indicators:* Confirm that PAPI units are aligned and functioning.

The designated Kievit, has an approximate **seven-minute time frame** to execute all these inspections and reports back to operational services and FMA. Collected RCR data is made into a condition report and communicated with LVNL for further communication with the relevant aircraft using the runway (Royal Schiphol Group, 2024c).

2.2.2 Evolving Methods and Global Reporting Format

RCR is required for aircraft departure and arrival and has historically been a critical aspect of runway safety, evolving from airport specific assessments to standardized global practices (Tuncal, Uslu, & Dursun, 2021). Traditionally, airport operations staff and pilots would report runway surface conditions using qualitative terms such as "good", "medium" or "poor braking action". These practices however, varied between regions and were prone to inconsistency, requiring a reform to address the large number of incidents caused by runway excursions: the cause of 179 deaths between 2010 and 2019 and over 4 billion dollars in consequential costs (Tuncal et al., 2021). Aircraft skidding off the runway, partly occurring due to a wrong perception of the runway condition, leads to significant physical, economic and reputational damage, accounting for almost a quarter of all airport incidents between 2005 and 2013 according to International Air Transport Association (2019). To address the inconsistencies of RCR and increase airside incidents, notably in winter conditions, the International Civil Aviation Organization (ICAO) initiated an effort to harmonize, resulting in the Global Reporting Format (GRF),

which became applicable worldwide on 4 November 2021 (International Civil Aviation Organization, 2021; Tuncal et al., 2021).

GRF standardised the reporting of runway surface conditions, enabling flight crews to accurately anticipate aircraft take-off and landing performance according to set codes, see Appendix B.1. At Schiphol Airport, runway condition reports are made during the described runway inspection procedure, see Section 2.2.1. As Schiphol has five runways opening and closing often throughout an operational day, depending on the weather conditions, runway condition reporting is often required. Condition reports are set up at Schiphol by driving a vehicle over the runway equipped with a sensor system containing various sensors per weather parameter. The sensor assesses the state of each runway third and reports the surface condition with a GRF formatted condition code. This code is dependent on various factors measured by the camera, see Appendix C.1. All the processes above are described in Schiphol's Internal *"Assessment and reporting of the runway condition user manual"* (Royal Schiphol Group, 2024b).

2.2.3 Sensor Based Runway Monitoring Technology

ICAO guidelines state that the approach to determining GRF codes by RCR is up to the airport themselves, prompting the adoption of various sensor-based runway monitoring technology across airports to support the airside personnel in determining the condition (International Civil Aviation Organization, 2021). Modern technology is enhancing the frequency and objectivity of runway reports, whilst airports are increasingly augmenting human inspections with sensor-based real-time monitoring systems, capable of reaching expectations (Vapola, 2021).

Schiphol Airport opted to utilize the Mobile Advanced Road Weather Information Sensor (MARWIS), a product by Lufft. MARWIS is a compact weather sensor that is mounted 1–2 meters above the runway surface. As the Kievit traverses a runway, MARWIS uses optical and infrared technology to scan the pavement directly below the vehicle, measuring a suite of parameters at up to 100 times per second, see Appendix C.1 for specifications (Lufft, 2025). A MARWIS-equipped vehicle essentially becomes *a driving weather station* feeding condition data into FMA control department, facilitating a precise description of a real-time profile of the runway able to, for example, distinguish that the far end of a runway is starting to ice over while the close end is merely wet. These sensor-based systems elevate the human inspector's observations with data, a step in the airside approach to data-driven decision-making.

The are also other mountable sensor systems available similar to MARWIS, such as the *Vaisala Mobile Detector MD30*, capable of similar sensor metrics. This system for example is used by other airports worldwide and is a market competitor of MARWIS (Vaisala, 2024). Airports also use other approaches, namely runway embedded sensor systems, though these are not relevant to drone approach scope of this study.

2.3 Autonomous Advancements and Capabilities of Drone Systems

Autonomous drone represents a rapidly advancing technological field, evolving towards the capability of complex tasks with minimal human intervention (Nonami, 2019). At its core, autonomous flight relies on integrated Guidance, Navigation and Control (GNC) systems, making drones aware of their live location enabling them to to position themselves as desired and execute flight routes precisely (Nonami, 2019). Autonomous drones are progressing through various stages of usability in society, from small-scale surveys to fully autonomous operations in populated areas having a societal impact (Rao, Gopi, & Maione, 2016). With state-of-the-art advancements allowing payload integration, drones are capable of a large set of implementations and are increasingly useful for complicated tasks, such as improving environment understanding (Hussein et al., 2021). Evolving capabilities provide a robust and reliable system for more specialised applications, including the potential for infrastructure monitoring (Nonami, 2019).

2.3.1 Flight Planning and Environment Perception

Whilst GNC system manage stable flight and mission execution, state-of-the-art drones also integrate onboard state estimation to regulate altitude and trajectory, with a accuracy error values in the order of 10^{-3} m (Mokrane, Benallegue, Choukchou-Braham, Hadri, & Cherki, 2022). This capability enables motion control and trajectory planning for safe and efficient flights, reinforced by Simultaneous Localization and Mapping (SLAM) techniques allowing drones to localize themselves and comprehend unknown terrain (Mokrane et al., 2022; Zhuang, Zhong, Xu, Tian, & Yu, 2024). Nowadays, modern systems do not even explicitly require Global Navigation Satellite System (GNSS) or Global Positioning System (GPS) input, as onboard visual sensors and LiDAR provide localization even in GPS-denied or texture-poor environments, showcasing state-of-the-art autonomous developments that would be required for safe operations in a high-risk environment like Schiphol.

By operating autonomously, drones must be able to plan and update their routes without human intervention. Path-planning algorithms are able to compute feasible flight paths whilst avoiding known obstacles, using onboard decision modules to select and sequence waypoints (Gugan & Haque, 2023). A described requirement for beyond visual line-of-sight autonomous drones is that they are tightly coupled with pre-planning, but also capable of decision-making to continuously re-evaluate their trajectory as the environment or objectives change, using onboard computation to adapt paths in real-time (Gugan & Haque, 2023).

2.3.2 Difficulties with Autonomous Adoptions

Automation introduces difficulties with regard to complex systems. In particular, the successful integration of autonomous technologies into real-world operations is not simply a matter of applying their proven technical capability (Gomez-Beldarrain et al., 2024, 2025). organisational adoption involves a sociotechnical entanglement where human roles, infrastructure, operational protocols, and stakeholder dynamics all shape whether and how automation can be meaningfully sustained. Previous studies at Schiphol Airport show persistent barriers to adoption, including stakeholder misalignment, lack of consensus on automation visions, and reliance on overly deterministic "plug-and-play" perceptions of technological (Gomez-Beldarrain et al., 2024, 2025). These findings suggest that beyond technical feasibility and pre-planning, successful deployment of autonomous systems demands careful orchestration of human, procedural, and infrastructural adaptations.

2.4 Safety Considerations of Drone Systems

As drones find themselves at the forefront of integration into airport environments, a surfacing challenge is their accompanied risks, and how they are to be mitigated. Positioning drones in the airport environment requires widescale risk assessment and development of systematic frameworks, of which a key aspect is understanding the safety capabilities of state-of-the-art drone systems (Basavaraju, Rangan, & Rajgopal, 2019).

2.4.1 Signal Jamming and GPS Spoofing

Two recurring risks identified in the academic literature regarding drones in airport environments are the presence of *unauthorised but fully operational drones* on the airside, and the presence of *authorized drones that have malfunctioned* while on the airside. In both scenarios, spoofing and jamming play a critical role (Lykou, Moustakas, & Gritzalis, 2020; Zidane, Silva, & Tavares, 2024).

On the one hand, signal jamming and GPS spoofing have become electronic countermeasures against unwanted drones. By overwhelming a drone's control or navigation signals, a jammer can force drones into fail-safe hovering modes or disabling its link to a malicious operator. GPS spoofing deceives a drone's positioning system by feeding it false coordinates, rendering its flying system disorientated and triggering fail-safes (Lykou et al., 2020). In experimental trials, researchers demonstrated that

spoofing a drone's GPS location to an airport's coordinates caused models to initiate emergency landings, indicating manufacturer-embedded no-fly zones can be leveraged to neutralize threats (Zidane et al., 2024). However, these techniques are not without limitations, as some drone models behave erratically and unpredictably under spoofing attacks, which might result in an unwanted drone being a larger problem than initially.

On the other hand, this protective description of signal jamming and GPS spoofing can also be seen as safety hazard: if drones are operated by an airport, they remain susceptible to signal jamming and GPS spoofing, and thus able to be compromised by external malicious parties or accidental interference. For instance, an attacker could jam the "wanted" drone's command-and-control link or its GPS receivers, causing the drone to lose navigation capability or enter a fail-safe mode. Loss of the control link is especially hazardous in an airport setting, as without communication, no intervention is possible and collision avoidance systems might not work, meaning potential distance from aircraft or critical infrastructure can not be assured, possibly leading to catastrophic consequences (Ferreira et al., 2022). GPS signals are also vulnerable to accidental interference, for example by unbeknown civilians surrounding Schiphol Airport accidentally interfering with aircraft signals, a serious concern for airports according to Pinker and Smith (1999).

Research has demonstrated that off-the-shelf drones using weak or unprotected protocols can be hijacked via simple attacks or spoofed signals (Lykou et al., 2020). To mitigate these risks, professionally operated drones tend to employ strategies involving redundant and resilient communication links, providing frequency hopping with the aim of reducing the chance that a single jammed frequency will sever control. Signals are typically encrypted and authenticated to make spoofing or takeover commands difficult (Lykou et al., 2020). Additionally, onboard sensors can help detect anomalies: if a drone's GPS data suddenly disagrees with inertial measurements, the system can recognize a spoofing attempt and trigger an alert or an emergency procedure. Overall, safeguarding communication and navigation links against signal jamming and GPS spoofing is a cornerstone in required risk management for airside drone integration (Basavaraju et al., 2019; Lykou et al., 2020).

2.4.2 Flight Safety and Risk Avoidance

Apart from external spoofing and jamming risks, there are also non-targeted risks— such as in air collisions —which could be critical for an airport's airside safety and operations (Pascarella et al., 2022). Integration strategies of drones at airports discuss various assurance methods that aim to assure a drone's cooperation with airside traffic, including flight planning safety and advanced collision avoidance systems in combination with proper operational protocols (Hussein et al., 2021). Fundamental to mitigating risks of drone flights is to ensure that they never fly in a dangerous vicinity of moving aircraft, support vehicles or critical infrastructure. Adding to this, Pascarella et al. (2022) pushes for the development of not merely risk avoidance but also risk-impact avoidance that limits airside chaos due to potential drone-related problems, such as a complete airport shutdown.

A method developed to ensure safe and secure drone flights, is a Designated Air Corridor (DAC), a flight perimeter in which a drone operates for a specific flight (Shvetsova & Shvetsov, 2020). A DAC can create segregated airspace for a drone alongside airport operations, avoiding path collisions, by determining a flight centre and radius, preventing the drone from exiting the calculated coordinates (Shvetsova & Shvetsov, 2020). A state-of-the-art innovation found in high-end drone systems is a safety supplement to DAC, increasing the potential for safe drone integration: a Collision Avoidance System (CAS). CAS consists of a sensor system, integrating onboard LiDAR and optical sensors able to detect obstacles in real-time. The implementation of dynamic path adjustment protocols that automatically modify the drone's trajectory when potential hazards are detected and operationalize a kill switch when required (Yasin et al., 2020). Research by Yasin et al. (2020) categorizes four different CAS methods, with the sense-and-avoid method particularly well suited for dynamic airport environments. Its real-time decision-making capabilities allow for immediate deviation from collision courses. An alternative option for drone integration is mitigating the flight risks completely by using a *root managing system*. This involves tethering a drone to a movement system or vehicle via cable, requiring ground infrastructure and thus mitigating many benefits offered by drones (Shvetsova & Shvetsov, 2020). Although a root managing system might not leverage all capabilities of a drone, it has shown to be a starting point for drone integration in high-risk areas.

Most high-end drones have integrated DAC and CAS, which would be a prerequisite for drone integration at Schiphol Airport. To evaluate these technologies, research has been conducted in both simulations and live trials to evaluate them in airport settings, demonstrating collision avoidance in airspace hosting aircraft (Alarcón et al., 2020). The results show that drones could reliably execute avoidance manoeuvrers when penetrating predefined buffers, thus concluding these systems are probable for safety standards in airport integration (Alarcón et al., 2020).

2.4.3 Disaster Impact at Airports

Even state-of-the-art risk avoidance is not capable of nullifying the possibility of a drone-related disaster at airports. To date, no recorded high-impact drone-related incidents have occurred at a major airport. Over the past eight years, there have also been no recorded accidents involving drones and commercial aircraft (Sun & Hubbard, 2025). However, the lack of historical incidents is no guarantee for the future. Growing drone activity requires a proactive position in analysing safety aspects to anticipate possible failures. Airports and air traffic agencies all over the globe are conducting risk assessments and trials for drone operations in controlled airspace. using simulations but also in field testing. These include controlled drone-aircraft collisions to explore worst-case scenarios, potential failure modes and calculating collision probabilities, synthesized in a drone safety assessment literature review by Asghari, Ivaki, and Madeira (2025). Asghari et al. (2025) prompts for secure selection of assessment method for each drone application, mentioning that unintentional malfunctioning in congested airspace could disrupt operations, cause economic losses, or even endanger lives. Sun and Hubbard (2025) describes that drones can present hazards comparable to bird strikes, a common danger in the aviation sector: unintentional flight into attractive jet engines could result in catastrophic consequences. Adding to this, bird strikes also form a potential problem for drones integration, as they congest airspace, and are known to interfere with airside activities. Wildlife management around Schiphol Airport is a crucial step in runway inspections, and will also play a role in the development of drone integration to prevent disaster impacts (Royal Schiphol Group, 2024c). Hazard and operability research has been done into drone systems in general high-risk environments, analysing processes and impacts using HAZOP methods, see Chapter 6 (Basavaraju et al., 2019).

2.5 Contemporary Drone Integration at Airports

Whilst drone integration at airports is a novelty, technical reports show that use cases are increasing. Before discussing use cases the regulation and emerging standards with regards to drone operations at airports are discussed.

2.5.1 Regulations and Emerging Standards:

Airsides are dynamically moving environments, consisting of various vehicles and aircraft, and thus a stage for significant risk for drone operations similar to urban areas. This requires a guarantee of safe airspace for operations according to Tran and Nguyen (2022). The presence of drones increases the collision chance with aircraft, thus requiring practical application protocols as well as a position in the aviation regulation, for making next-generation airport operations possible Shvetsova and Shvetsov (2020). As Edelman et al. (2023) states, "Connecting autonomous drones to ground operations and services is a prerequisite for the adoption of scalable and sustainable drone services in the built environment", prompting the need for emerging standards of operation by regulatory reforms. At Schiphol, airspace activity is regulated by national jurisdiction and manifested by LVNL, which enforces a CTR policy that permits a maximum of two drones operating in constant communication with air traffic control tower within the airspace at any given time (LVNL, 2024).

Yet as airports develop, so are international guidelines and regulations. The ICAO emphasizes that aerodromes represent *the most complex environments* for drone systems, and that integration efforts

must avoid degrading safety levels or disrupting existing operations (International Civil Aviation Organization, 2017). ICAO's guidance promotes a risk-based framework for drone integration into non-segregated airspace, advocating for clearly defined roles among stakeholders such as Air Traffic Control (ATC) and operators as a prerequisite for safe drone operations at airports. This underscores the necessity for both technical protocols and institutional trust to evolve in parallel before drone operations can be standardized (International Civil Aviation Organization, 2023).

At Schiphol Airport, the ATC party LVNL operates under IenW and European Union Aviation Safety Agency (EASA) regulations within a predefined CTR zone, that LVNL does not establish itself but is continually helping refine (European Union Aviation Safety Agency, 2021; Inspectie Leefomgeving en Transport, 2025). Although LVNL merely enforces the jurisdiction, it retains full responsibility for managing drone operations within the CTR airspace. A central challenge for the organisation is developing drone integration into their airspace. A development they put a lot of thought into, has been trying to constitute what a "drone" is in current jurisdiction, see Appendix I.2. Since drones currently are treated as aircraft, yet lack transponders, complicate their identification and tracking, see Appendix I.2. With regards to drones and what is allowed in the CTR, LVNL adopts a three-tier classification: the *open category*—hobby drones under 250g— which are prohibited in the CTR due to their unmanageable nature; the *specific category*—operational drones such as would be used for RCR—and the *certified category*—future high-performance platforms like drone taxis— which have not yet met aviation certification standards (LVNL, 2025). Because IenW and EASA regulation enforces these particularly rules, any drone activity in the CTR——even for LVNL's own system improvement——demands their adherence European Union Aviation Safety Agency (2021); Inspectie Leefomgeving en Transport (2025).

2.5.2 Real-World Airport Drone Use Cases:

The following paragraphs include examples of real-world drone use cases, highlighting the state-of-the-art with regard to actual on-site developments. So far there are no noted continuous operational drones at any major airports. The use cases underscore a few common themes. First, safety and coordination are important—-every trial involved careful planning in closed-airspace. Second, the technology has matured to the point where data quality is high—drones can produce detailed results, detect small hazards and are seen as a beneficial development. Third, there is a clear interest from airports around the world in harnessing drones to improve efficiency. Schiphol's vision of drone usage in the airside operations aligns with the industry trend where automation is entering their airspace, the following are state-of-the-art examples.

Schiphol Airport - Taxiway and Critical Infrastructure Inspection 2020

As stated by Royal Schiphol Group (2020a) and LVNL (2020).

On June 2020, Schiphol in combination with LVNL conducted a week-long trial deploying drones equipped with high-resolution cameras to survey taxiways, small buildings, and aircraft exteriors, and to transport light cargo such as maintenance parts and de-icing supplies within the airside environment. Authorized under a temporary regulation from IenW, all flights were manned by CTR certified pilots in continuous coordination with air traffic control, strictly confined to predefined DAC away from active runways, and featured automatic RTH and EL failsafe upon link loss. The trial demonstrated that even in a busy airport, drones can aid inspection methods by generating detailed imagery for pavement condition efficiently and conducting Foreign Object Debris (FOD) inspections from an effective height, whilst reducing personnel exposure to runway hazards. This highlighted the potential and required development of drones at Schiphol Airport.

Paris Charles de Gaulle (CDG) - Drone Pavement Inspection 2016

As stated by Airsight GmbH (2016).

One of the earlier large-scale drone trials was conducted at CDG, where an untethered drone was operated for a runway pavement survey. This project aimed to see if a drone could capture high-resolution imagery of the runway surface to detect cracks or pavement issues, complementing the usual

visual inspections done by staff driving on the runway. A safety case was developed and approved by the airport authority and ATC, ensuring thorough coordination. The drone flew over 200,000 square meters of runway, planned to minimize impact and exiting well before any aircraft congestion. The data collected were processed into a georeferenced map of the runway, allowing engineers to identify pavement distresses in a fraction of the time it would take for a manual walking inspection.

Memphis International Airport (MEM) - BEYOND Program 2020-

As stated by Memphis-Shelby County Airport Authority (2024).

A multi-year drone trial program is being executed at MEM in the United States. Since 2020, MEM in collaboration with FedEx logged roughly 2,000 successful flights within controlled airspace. These trials focused on four areas: *runway FOD detection, perimeter and security patrols, aircraft inspections, and on-demand parts delivery on the airfield*. These inspections demonstrated the potential to improve turnaround times across all areas. All MEM trials have been conducted under safety protocols developed with their federal aviation administration. The airport obtained special approvals to fly in the airspace and implemented communications and oversight in collaboration with their ATC. Early tests were first done off-airport at a nearby site to validate safety before moving on-airfield. In one instance, when an unrelated rogue drone was detected near the airport, the established communication network allowed authorities to swiftly confirm it was not part of the approved program and take action. So far, MEM reports no safety incidents within their multi-year trial, whilst outcomes prove that drones can execute routine airfield inspections reliably. The ongoing trials at MEM are actively informing their federal aviation administration on developing policies for regular drone operations at airports nationwide.

London Heathrow Airport - High-Intensity Autonomous Drone Operations Trials)

As stated by Carmenta (2025).

In late 2024, London Heathrow Airport hosted *High-Intensity Autonomous Drone Operations* trials under the United Kingdom's Innovation Agency to demonstrate routine beyond-visual-line-of-sight drone flights within the airport's flight restriction zone. Using uncrewed ATC, autonomous drones conducted *airside surveillance and infrastructure inspections* without impacting active runways. Flights were pre-authorized, confined within dynamic geofences and monitored in real-time. Simulated traffic injections tested real-life conflict-management protocols, while built-in fail-safes showed that any deviation triggered an immediate safe landing procedure. The trials confirmed that with robust coordination and emergency procedures, drones can safely augment security and maintenance tasks in one of the world's most complex airspaces—prompting further research into routine airport operations under future regulations.

Hong Kong International Airport - Airfield Lighting & ILS Inspection 2023

As stated by Civil Aviation Department, The Government of the Hong Kong Special Administrative Region (2023).

In August 2023, Hong Kong International Airport's Civil Aviation Department piloted a drone-based flight inspection of its Instrument Landing System (ILS) and runway lighting during a night-time runway closure. A small drone, flown at low altitude by certified operators, carried photometric sensors to measure ILS signal quality and light alignment, producing data that matched traditional manned flight inspection results. Coordinated with ATC and supported by emergency "kill-switch" protocols, the drone executed multiple passes in under 30 minutes—significantly reducing their closure time, cost, and carbon emissions compared to a conventional inspection. This trial demonstrated that drones can perform critical surveys on runways, offering a scalable method to increase inspection frequency while minimizing operational disruption.

2.6 Identified Knowledge Gaps

Despite growing literature on the deployment of drones within airport environments, knowledge gaps persist in various aspects of autonomous drone integration at airside. Existing literature tends to emphasize general usability and trials, often bypassing the complex operational dimensions and impact on day-to-day airside safety at large international airports. The following gaps highlight the necessity and originality of this thesis, which focuses on developing a case study of an autonomous drone approach to RCR at Schiphol Airport.

1. **Lack of Context-specific Risk Assessment at Airports:** While risk factors such as mid-air collisions and communication failures are acknowledged in state-of-the-art drone research, context-specific drone risk assessments tailored to airside environments are lacking. In particular, current studies tend to generalize risk scenarios detached from the realities of airside, and there is a notable absence of HAZOP-based studies explicitly applied to autonomous drones operating near active runways. The existing examples of HAZOP in drone contexts deal with industrial or urban applications and do not address the interdependencies of an airfield environment, which is not surprising as use cases demonstrate highly segmented trials and no indication of research into repetitive use. This knowledge gap could be bridged by conducting a tailored HAZOP analysis specifically adapted to a repetitive runway task.
2. **Lack of Operational Flight Planning and Protocol Development:** Existing studies demonstrate safe trials under highly controlled conditions but lack practical frameworks for embedding autonomous drones into continuous, high-traffic airport environments. Challenges such as mission scheduling around aircraft movements, runway constraints and real-time coordination remain unexplored. Airports like Schiphol operate under strict rules, yet there is no clear methodology for working consistently with routine autonomous drone operations within these rules. This knowledge gap could be bridged by developing systematic trajectories accompanied by flight protocols.
3. **Need for Stakeholder Vision and Understanding Development** Sociotechnical barriers — such as misaligned visions among stakeholders, required changes to standard operating procedures, and human trust in automation — are noted but not systematically analysed in the context of specific case study. This knowledge gap could be bridged with research that involves exploring wider autonomous drone implications, involving airport stakeholders to showcase the potential of autonomous drone integration into the operational airside.
4. **Lack of System Analysis and Performance Metrics for Specific Use-Cases:** While sensor-based runway monitoring technology and advancements in drone technologies are documented, there is little research into how these subsystems could perform under repetitive use in the airside environment. Where existing use cases elaborate on their objective and findings, they do not highlight research steps made that could aid with future decision-making with regard to drone operations at airports. This knowledge gap could be bridged by analysing the wide-scale system involving autonomous drones and assess their reliability and performance.
5. **Lack of Autonomous Implementation:** Literature describes the advancements of autonomous drone technology but does not go into the analysis of their benefits for consistent airside operations. All discussed use cases are human operated drone flights. As the state-of-the-art describes RCR would lend itself to an interesting exploration of autonomous operations, and a potential to bridge this knowledge gap.

3 Research Design

This chapter outlines the design of the thesis, by first describing the research goal and the main question serving as a guiding query. Following this, the framework used to answer this question is described, followed by the four sub-questions and their place within this framework, each designed to address a specific research dimension: *reliability*, *effectiveness* and *safety*.

3.1 Research Goal

This research is executed as an graduate internship in collaboration with the Infrastructure Innovation Team of Royal Schiphol Group. The initial question from Schiphol team, fundamental to this research's design was: *How can drones play a role in the autonomous future of Schiphol's airside?*

Over the six-month duration of the internship, the study aims to answer that question by developing a case study for autonomous drones at Schiphol's airside. Preparatory research involved mapping existing airside operations that lend themselves to automation, see Appendix A.1. From this exploration a focus landed on RCR, a critical airside inspection task identified for its repetitive nature, linear workflow and potential for efficiency improvements. The research goal of the case study is to explore technical *reliability*, operational *effectiveness* and risk *safety* factors essential for drone-based autonomous RCR at Schiphol. While RCR serves as the focus, the use case development and risk assessment aim to be applicable to other autonomous drone developments at Schiphol Airport. The main research question is formulated to capture the overarching goal of developing a case study within Schiphol Airport's operational environment, emphasizing the relevance of the three dimensions: *reliability*, *effectiveness* and *safety*:

"How can drones be utilized reliably, effectively and safely within Schiphol Airport's operational environment to automate runway condition reporting?"

3.2 Defining Reliability, Effectiveness and Safety

To ensure clarity throughout the study, this thesis explicitly defines three aspects guiding the exploration and development of drone-based autonomous RCR. Each represents a distinct yet interdependent dimension of the case study, enabling a scoped and structured research design.

- *Reliability* is defined as the consistency and repeatability of a drone system's RCR performance under varying conditions over time. It indicates the expected percentage of days to which RCR data collection would be free from error and can be depended upon to function as intended during operational use.
- *Effectiveness* is defined as the degree to which a system can perform RCR whilst minimising mission time in accordance with operational constraints and requirements. Effectiveness reflects how well the drone system would achieves its intended purpose comparable to current inspections while maintaining procedural integrity and operational practicality.
- *Safety* is defined as the extent to which a drone system can perform RCR without a high probability of introducing unacceptable consequences to the airside environment. The safety dimension reflects safety risks causes by drone design deviations, their probability of happening in an operational year, and their severity for Schiphol's airside.

3.3 Framework

To systematically explore the main research question, this study adopts a Stage–Gate process framework, to ground itself in innovation management guidelines, emphasizing concept development through staged stakeholder validation and iterative improvement (U.S. Department of Energy, Industrial Technologies Program, 2007). This framework is extended by *Cooper's NexGen Stage–Gate principles*, calling for exploratory research approaches, multidisciplinary teams, and lean, scalable deliverables (Cooper, 2008). Tailoring the Stage–Gate process framework to this study resulted in three research stages consisting of answering sub-questions, and validating outcomes *per gate*,before progressing on to the next stage. The idea of this approach is to assure a concepts development is aligned with stakeholder insights.

- **Stage 0 consists of the preliminary exploration:** conducting a literature review and stakeholder discussions to map existing airside operations ripe for automation and identify existing drone-based concepts. These early insights were discussed with Schiphol stakeholders through a three-week process, helping to refine the research scope and select RCR as the focus.
- **Stage 1 focuses on reliability:** The question *"Can an autonomous drone system work at Schiphol Airport?"* is asked, aimed at evaluating the wide-scale system and drone platforms against described Schiphol-specific criteria and weather. At Gate 1, expert interviews are conducted to validate reliability by technical feasibility and before progressing to stage 2.
- **Stage 2 focuses on effectiveness and safety:** The questions *"How would a drone execute this operation at Schiphol?"*and *"What are the risks involved?"* are asked ans approached by developing a flight trajectory and operational plan, followed by conducting a HAZOP-based risk assessment to uncover hazards and propose mitigations. At Gate 2, the design and pre-identified risks are validated by stakeholder representatives in the HAZOP safety meeting as well as subsequent review meetings resulting in iterative improvement.
- **Stage 3 synthesizes insights from stage 1 and 2 into a visualisation model:** This final stage, though not subject to a formal gate review, produces a model of the autonomous RCR system, showcasing the innovation development for stakeholder comprehension and future development.

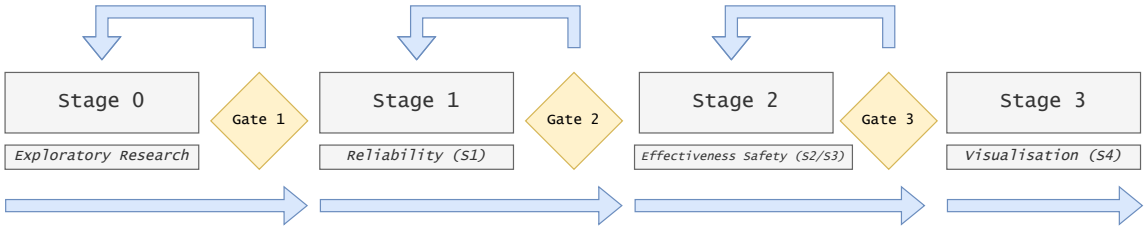


Figure 3.1: Stage-Gate Framework Flow Diagram

3.4 Sub-questions

The various stages of the research framework are segmented into four research questions, to which each chapter in this study is dedicated.

S1: "What technical specifications are required for a drone to reliably perform autonomous runway condition reporting under Schiphol Airport's environmental conditions?"

This sub-question aims to determine what drone system is reliable for conducting RCR in the Schiphol airside and to what extent. Providing benchmarks for subsequent process development and laying the ground for trajectory and protocol development.

- **Method:** Answering this sub-question involves technical feasibility analysis, starting with a stakeholder analysis and initial system description deriving performance criteria, drawing on literature and stakeholders insight. Following this, a survey is executed identifying a shortlist of commercially available platforms capable of meeting baseline criteria. Drone systems are compared using

a Weighted Decision Matrix (WDM) by their raw specifications and scored according to weights that reflect Schiphol's priorities, as validated in four semi-structured expert interviews. Finally, a *deemed reliable drone* is analysed according to Koninklijk Nederlands Meteologisch Instituut (KNMI) weather data and analysed for its internal system design.

- **Data Source:** Technical specification manuals for DJI Matrice 300/350RTK/600, Freefly Alta X and MARWIS sensor (DJI, 2023, 2025; Lufft, 2025); KNMI archives (KNMI, 2025); Schiphol runway and operational reports (LVNL, 2024); Four expert interview transcripts Appendix E.
- **Tools:** Spreadsheet models (Excel) and Python (pandas, NumPy) for the decision-matrix computations; Python (pandas, Matplotlib) for processing and visualizing weather data trends;

S2: "What specific autonomous flight trajectory and operational protocols are required to effectively perform runway condition reporting at Schiphol Airport?"

This sub-question aims to establish an effective autonomous drone flight trajectory and operational protocol design tailored for conducting RCR at Schiphol's Polderbaan. This sub-question lays the ground for the subsequent HAZOP and is iteratively improved using expert validation in gate 3.

- **Method:** First, Schiphol's RCR procedures are translated into a mission objectives. Second, runway constraints are identified and combined for trajectory design. Third, optimal locations for the drone hubs and trajectory routes are determined with the objective function. Fourth, a flight route is developed, which in subsequent steps can be analysed for its risks. Fifth, the operational protocol is defined by trigger conditions, and flight planning steps and embedded in safety procedures.
- **Data Source:** Schiphol RCR manual and LVNL guidelines (Royal Schiphol Group, 2024c), ICAO Annex 14 Vol. I and EASA runway design standards (European Union Aviation Safety Agency, 2021; International Civil Aviation Organization, 2017). Schiphol Specifications (LVNL, 2024)
- **Tools:** Photoshop, GIS.

S3: "What operational risks and safety impacts arise by using autonomous drones for runway condition reporting, and how can these risks be mitigated?"

This sub-question aims to evaluate the potential risks and safety impacts associated with the deployment of autonomous drones at Schiphol Airport according to the developed trajectory and protocol.

- **Method:** Answering this sub-question involves a structured HAZOP study to uncover and evaluate the operational risks and safety impacts of deploying autonomous drones for RCR at the Polderbaan. First, a multidisciplinary safety meeting — comprising key stakeholders from Royal Schiphol Group and LVNL systematically review the trajectory developed according to a HAZOP procedure. For every identified deviation, the team discuss causes, consequences and initial mitigation proposals, then scores probability and severity on a tailored five-level scale. Trajectory improvements are iteratively made, followed by a final four targeted review sessions, planned to validate and refine the findings and recommended controls as gate 3.
- **Data Source:** HAZOP Guidelines (Rausand, 2011); HAZOP safety meeting, see Appendix H.2 and review meetings see AppendixI.2.
- **Tools:** Excel for Qualitative data processing.

S4: "How can a visualisation model demonstrate the integration of autonomous drones into Schiphol Airport's airside for runway condition reporting, and what insights can be drawn from data-driven visual analysis?" This sub-question aims to develop and assess a one-day visualisation model that integrates autonomous drone operations into Schiphol's airside environment. Rather than simulating full system dynamics, the model uses historical operational data to depict how drone-based RCR procedures could function in context.

- **Method:** Answering this sub-question involves the development of an agent-based visualisation model using Python's MESA package. This model combines the designed behaviour of six drone trajectories developed, to simulate its behaviour alongside Kievit operations and Aircraft traffic.
- **Data Source:** Schiphol Aircraft Transponder Data; Schiphol Kievit Vehicle Transponder Data.
- **Tools:** Python for Data analysis and MESA for agent-based modelling

4 Technical Feasibility Analysis

Developing a case study for an autonomous RCR requires analysing drone systems for their operational specifications, to assess their performance reliability. This chapter deals with those aspects by conducting a *technical feasibility analysis*. The scope is confined to determining whether commercially available drones are able to reliable conduct RCR using a dual drone set-up in varying Schiphol weather conditions and if so, *which* drone system should be selected for the further development of the case study.

4.1 Goal and Motivation

The goal of this technical feasibility analysis is to identify a technically feasible drone-sensor setup that can reliably perform runway condition reporting autonomously at Schiphol Airport. Given the complexity and high-risk nature of the airport environments, selecting a reliable drone system demands an understanding of both specific capabilities and how environmental weather impacts performance.

The setup for this analysis is based on principles laid out by Pearson et al. (2020), who emphasise that feasibility studies should assess the practicality, acceptability, and contextual fit of innovation within its real-world setting. Pearson et al. (2020) states that feasibility research serves to reduce uncertainties around implementation strategies, by identifying technical constraints tailored to specific operational environments. This approach is relevant to the complex system of Schiphol Airport. In developing this analysis, inspiration is drawn from both guidelines by Pearson et al. (2020), as well as a drone-specific system design by Smyczyński, Starzec, and Granosik (2017). The approach to weather analysis takes inspiration from drone feasibility analysis by Gao et al. (2021). These works highlight the value of evaluating both technological specifications and environmental conditions concurrently, reinforcing the methodological relevance of the approach taken in this study.

This research aligns drone technology directly with Schiphol Airport's environmental context, bridging a gap in current literature with regard to contextual specificity. The validation process, executed through semi-structured expert interviews, aids the analysis by not only making sure the system is theoretically sound but also evaluating if it is practically implementable and potentially beneficial in improving RCR.

4.2 Approach

1. **Stakeholder Analysis:** Identification of key parties relevant to the case study.
2. **System and Criteria Overview:** High-level system description, including relevant Schiphol criteria and a shortlist of suitable commercially available drones.
3. **Comparative Assessment:** Evaluation of candidate drones using a WDM based on technical specifications and weighted criteria.
4. **Expert Validation:** Refinement of criteria and assessment through four Human Research Ethic Committee (HREC) approved expert interviews, see Appendix E.
5. **Weather Impact Assessment:** Analysis of selected drone's operability under historical Schiphol weather data from KNMI, assessing performance reliability.
6. **Drone–Hub Interaction:** Technical feasibility overview describing system integration between drone, sensor payload, and hub infrastructure.

4.3 Stakeholder Analysis

The integration of autonomous drones into airside operations not only represents a technical transition, but also a significant organizational transition (Gomez-Beldarrain et al., 2024). This stakeholder analysis serves to identify and assess the parties that either influence or are influenced by the innovation introduced in this case study. Using a power–interest grid, stakeholders are classified according to their capacity to impact the development and operation of drone-based runway inspections (power) and their level of engagement and benefit of successful adoption (interest), according to guidelines described by Jepsen and Eskerod (2008).

Understanding stakeholder positioning in terms of power and interest is beneficial for exploring autonomous drone RCR, guiding what stakeholders to approach during the study. It also aids in formulating targeted integration strategies for Schiphol in the concluding chapters of this thesis. The stakeholder analysis identified the following parties and their position within the power-interest grid, see Figure 4.1.

- **Asset Management (ASM) – Royal Schiphol Group**: As the stakeholder responsible for airside infrastructure and maintenance, Asset Management (ASM) plays a role in facilitating the physical integration of drone systems, particularly in the development and upkeep of ground-based drone hubs. ASM has an interest in the successful operation of their maintained infrastructure, but does not directly benefit from autonomous RCR operation, and holds moderate power through control over the infrastructure-related decision-making. The Infrastructure Innovation team within ASM has been actively involved throughout this research and is consistently integrated into the stage-gate innovation process outlined in Chapter 3.
- **Airside Operations (DDO, FMA, Havendienst, Kievitten) – Royal Schiphol Group**: These four stakeholders form the core operational unit of Schiphol Airside, including Day-to-Day Operations (DDO), FMA, the Havendienst (Airside Service), and Kievitten (Airside Inspection team). With responsibility of airside processes during operational hours, their functionalities translate into high power over the integration of autonomous drones, whilst the innovative development of drone-based runway inspections is of high interest, due to its potential for airside process improvements. These stakeholders are actively engaged in autonomous drone development, and play an important role in the future of autonomous drones at Schiphol Airport.
- **Airside Process Management – Royal Schiphol Group**: Airside Process Management (APM) oversees end-to-end airside process chains, including taxiing procedures and aircraft policy. Service owners within this stakeholder domain are crucial for drone trajectory planning and safety coordination development. While their power is primarily procedural, their operational policy development is crucial for the innovations development and successful integration. As drone integration affects this stakeholder less directly, it has a moderate interest in the innovation. Throughout the case study APM is engaged in policy development queries and use case exploration.
- **Dutch Air Traffic Control – Luchtverkeersleiding Nederland (LVNL)**: This stakeholder holds regulatory and operational authority over Schiphol's airspace, including drone integration at airside. LVNL has previously led drone inspection trials at Schiphol and is responsible for certifying any structural integration into airside operations. Given their control over airspace safety and real-time traffic coordination, and their continuous focus on the future of drones in the Dutch airspace, LVNL exhibits both a high power and a high interest. Their cooperation is essential for legal and procedural approval, and the stakeholder is engaged throughout this study.
- **Regulatory Authorities – Ministry of Infrastructure and Waterstaat and EASA**: National and European regulators, including the Dutch IenW, and the EASA, hold overarching judicial authority on drone flight. Although these stakeholders are not directly involved in operational implementation, their legal mandates translate into significant power. As autonomous drone integration plays a minor role in their tasks, it translates to low interest. As these stakeholders are critical to enabling legal drone integration, their regulations must be addressed accordingly.
- **Airside Infrastructure Contractor – Heijmans B.V.**: This stakeholder holds the contract for airside infrastructure at Schiphol Airport, covering the maintenance and management of runways.

While not a formal decision-maker, the contractor's operational relevance is significant: the development of autonomous runway inspections could potentially benefit maintenance procedures' efficiency. As indicated in interviews, see Appendix E.3.1, Heijmans exhibits an interest in the development of drone integration. This stakeholder should be regularly informed and engaged in development cycles, to benefit overall airside efficiency in the future.

- **Dutch Drone Delta (DDD) - Innovation Consortium:** As a collaborating organisation effort, with strong ties with both industry and government, this stakeholder is aimed at accelerating the safe and scalable integration of drones into Dutch airspace. While DDD holds no formal power over operational or regulatory decision-making at Schiphol Airport, it has a high interest in leveraging innovative drone use cases to promote the normalization of operational drones. Through its coordination role and close collaboration with public authorities, DDD serves as an enabler of drone integration development and is engaged in the case study for use case exploration and policy-shaping dialogue

Beyond these parties, there are additional stakeholders that fall outside the scope of this case study. These include *aircraft companies*, who would benefit from more efficient runway inspections, *competitor airports*, who could be collaborated with, but also other further Schiphol stakeholders —such as the *Data & IT department*, whose functionalities could aid autonomous drone development and play a role in future developments.

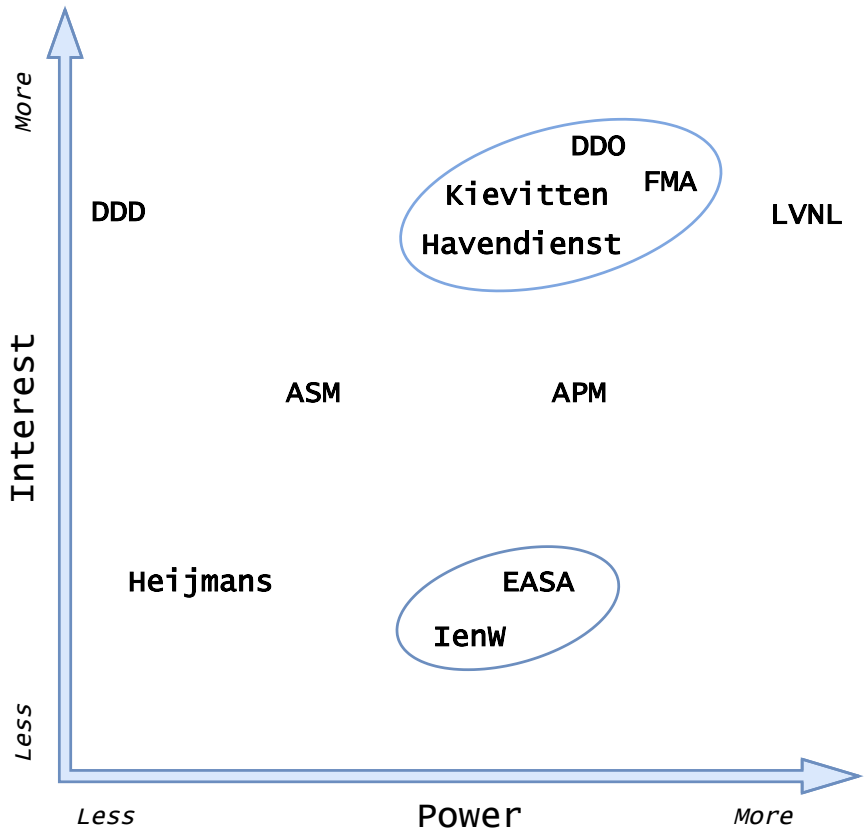


Figure 4.1: Power-Interest Grid

4.4 System Overview

4.4.1 Drone Runway Condition Reporting System

Describing the overall system of the autonomous drone RCR helps identify the criteria for evaluating the feasibility of drone systems. In general, a drone system comprises two main elements: the air component (the drone) and a ground component (handler or docking station), which must maintain continuous interaction to ensure reliable, effective and safe operation (Hussein et al., 2021). This research proposes a point-to-point drone network, a design that consists of intermediate charging stations along the flight path, which has been shown by Pinto and Lagorio (2021) to improve system efficiency in drone trajectory networks. In RCR a point-to-point network translates to a dual docking station setup, where docking stations or *Ground Hubs* are positioned at either end of a runway, functioning as both a departure and arrival station, and as a charge station. These functionalities are according to state-of-the-art docking station development (Grlj, Krznar, & Pranjić, 2022). Together the hubs and the drone make up the *drone system*. In this research a drone system design mentioned by Hussein et al. (2021) is extended by two components relevant for theRCR use-case: the mission target—the to be inspected runway— and the environment in which this happens. The widescale diagram, consisting of the three described sections can be seen in Figure 4.2.

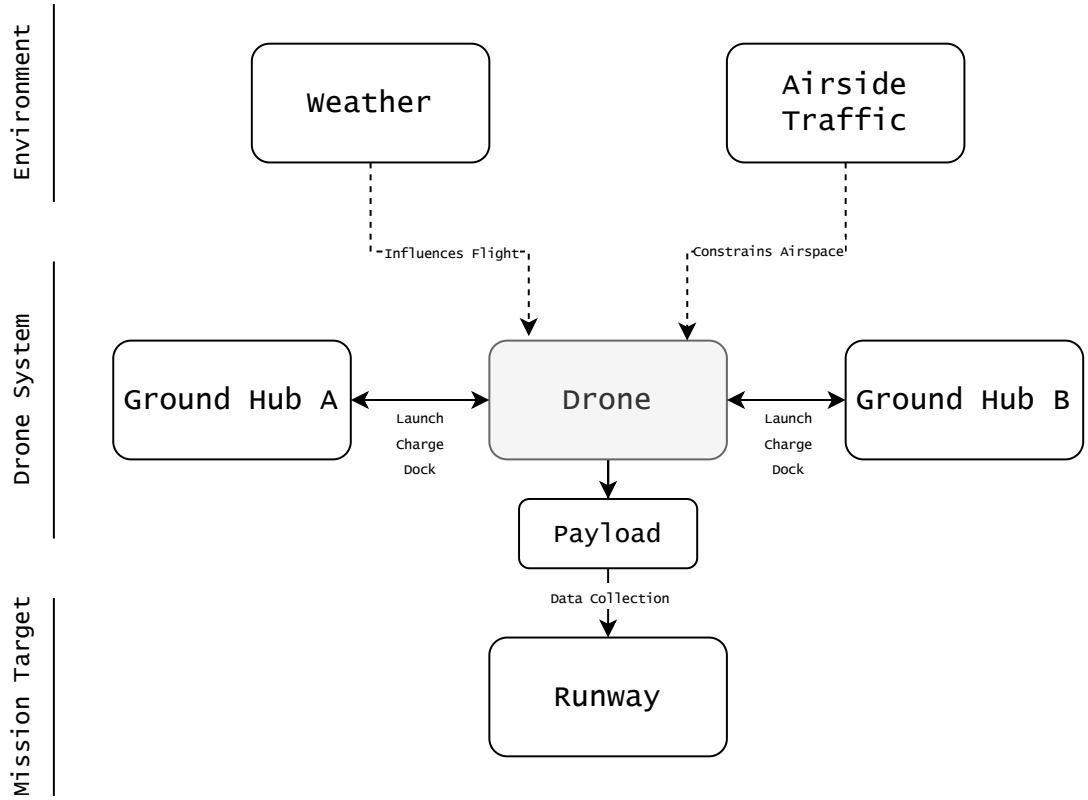


Figure 4.2: RCR System Diagram

4.4.2 Criteria Specification

In demanding environments, drones must meet performance expectations to ensure reliable operation. Therefore each section of Figure 4.2, environment (E), drone system (DS) and mission target (MT), is taken in account for guiding the identification of relevant criteria.

- **Environment Criteria** *(temperature, wind, wind gusts and precipitation)* affect drone endurance and control, and are therefore identified as criteria for selecting a feasible drone system (Gao et al., 2021). Ambient temperature range impacts usability and performance, with extreme heat shortening flight duration due to battery degradation (Leng, Tan, & Pecht, 2015). Wind effects can destabilize drones, causing problems in the airport environment according to (Hristozov & Zlateva, 2018). Precipitation has been shown to to have effects on aerodynamic performance and if prolonged affect drone flight internal systems (Dhulipalla, Samad, & Hu, 2024).
- **Drone System Criteria** *(battery Life and flight speed)* impact the usability of a drone system and are key in evaluating feasibility: battery life determines if a drone system is able to complete a RCR trajectory, and the flight speed determines potential efficiency improvements over current practices (Pinto & Lagorio, 2021).
- **Mission Target Criteria** *(flight accuracy and payload capacity)* determine the feasibility of drone RCR using MARWIS and the quality of data collected. Sub-metre drone positioning accuracy is essential for maintaining a correct flight path and ensuring that MARWIS collects reliable data. Flight accuracy is important for successfully landing on hubs (Pinto & Lagorio, 2021).

Metrics ranges for the identified criteria are retrieved from three main sources. Their respective rationale for determining criteria metric value is seen in Table 4.1. The three sources are the following:

- **Schiphol Weather Data:** Using weather data specific to the Schiphol Airport region, made available by KNMI (2025), metric ranges for the criteria *temperature, wind, wind gusts and precipitation* can be determined. This weather data source is also used in subsequent weather analysis. Results of the weather data exploration can be seen in Appendix D.1
- **Schiphol Runway Properties:** Properties specific to Schiphol runways — relevant for drone system endurance — are fundamental in evaluating a drone system's battery life. See Appendix C.2 for an overview of the runway specifications.
- **MARWIS Sensor Specifications:** Currently, Schiphol Airport uses a car-mounted MARWIS sensor for runway condition reporting. The specifications of this sensor—such as its size and weight—provide benchmarks for the technical requirements of the drone system. For complete sensor specifications, see Appendix C.1. For more information on MARWIS see Section 2.2.3.

Table 4.1: Identified Criteria

Cat.	Criteria	Metric	Value	Rationale
E	**Operating Temperature**	Ambient temperature range (°C)	$\geq$–10°C $\leq$+50°C	Schiphol's climate extremes, determined using decadal temperature data (KNMI, 2025), see Appendix D.1
	Water Resistance	Ingress Protection (IP) rating	$\geq$ IP43	Able to withstand at least the max average daily precipitation of Schiphol environment, see Appendix D.1.
	Wind Resistance	Max. sustained wind speed for operation (m/s)	$\geq$7.5m/s	Able to withstand at least the average hourly max wind speed at Schiphol Airport, see Appendix D.1.
DS	**Battery Life**	Consecutive operable flight time with payload(m)	$\geq$15min	Able to complete at least the max runway length, see Appendix C.2, at 20m/s as per current RCR, see Section 2.2.1
	Flight Speed	Min. horizontal cruise speed (m/s)	$\geq$15m/s	Able to at least fly as quick as current approximate RCR interval, see Appendix 2.2.1
MT	**Flight Accuracy**	Horizontal/vertical positioning error (m)	$<$ 0.10m	In line with the MARWIS 10% error margin, see Appendix C.1.
	Payload Capacity	Min. payload mass (kg)	$\geq$1.7kg	Able to at least carry the MARWIS sensor.

The specification deliberately excludes several criteria that lie beyond the scope of this analysis. First, *cost* is not considered: all commercially available systems explored fall within the budget range for Infrastructure Innovations projects at Schiphol Airport, rendering price differentiation irrelevant to the selection process. Second, *usability* has been omitted, as all shortlisted drone systems are identified for their capabilities for autonomous flight and docking-station integration. For this same reason *safety* has been omitted as a criterion, as the drones are all capable of comparable CAS systems. An aspect according to safety which is interesting but omitted is the component manufacturers not being native to Schiphol or direct partners, causing a potential issue falling outside of the scope of this research, see Section 10. Finally, modular capabilities—the ease of integrating alternative payloads for various infrastructure innovations tasks—are recognised as valuable for multi-mission versatility but is not a formal criterion, given the study's focus on RCR. Modularity is taken into account in the payload capacity, as a higher payload capacity is seen as beneficial for future modular adaptions.

4.4.3 Commercially Available drones

Based on the identified criteria a search was conducted to pinpoint commercially available drones that meet the expectations for RCR at Schiphol Airport. Table 4.2 presents an overview of key specifications for the shortlisted drone platforms. This preliminary comparison serves as a foundation for further comparative steps. DJI Matrice 600PRO has been selected as a candidate—even though it does not have the desired water resistance criteria—as it comes with significant payload benefits.

Table 4.2: Shortlist Commercially Available Drones (DJI, 2016, 2020, 2023; Freefly Systems, 2019)

Model	Size (L×WxH)	Horizontal Speed	Battery Life	Weight	Payload Capacity	Operating Temperature	Max. Wind Resistance	Hovering Accuracy	Water Resistance
DJI Matrice 600 Pro (DJI Enterprise)	1668 × 1518 × 727mm	18 m/s	32-min	9.5 kg	6 kg	-10° C to 40° C	8 m/s	Vertical: 0.50m, Horizontal: 1.5m	-
DJI Matrice 300RTK (DJI Enterprise)	430 × 420 × 430mm	23 m/s	55-min	6.3 kg	2.7 kg	-20° C to 50° C	12 m/s	Vertical: 0.15m, Horizontal: 0.10m	IP45
DJI Matrice 350RTK (DJI Enterprise)	430 × 420 × 430mm	23 m/s	55-min	6.5 kg	2.7 kg	-20° C to 50° C	12 m/s	Vertical: 0.10m, Horizontal: 0.10m	IP45
Freefly Alta X (Freefly Systems)	1415 x 1415 x 387mm	20 m/s	50-min	10.9 kg	15.1kg	-20° C to 50° C	10 m/s	Vertical 0.10m, Horizontal: 0.10m	IP43

4.5 Comparative Assessment

Recognizing that none of the drones are superior in every aspect, a comparative assessment is conducted. This analysis identifies the most suitable drone system for Schiphol Airport by evaluating each drone against the specified criteria.

This comparative assessment is done using a WDM, a qualitative technique effective in ranking multi-dimensional options, consistent with decision-making frameworks in engineering design (Olabanji & Mpofu, 2014). WDM is the evolution of a method developed by Pugh (1991), widely recognised for its ability to systematically compare design alternatives. Though it is important to recognise shortcomings of WDM: as stated by Olabanji and Mpofu (2014, p. 266) drawbacks include "the assumption of a linear relationship for parameter weights and the manipulation and misjudge of weights and scores". Therefore, in this study, the score ratings are validated by two drone experts to ensure that the evaluation accurately reflects the practical challenges of the Schiphol, see Appendix E.4.5.

Parameters have a rating ranging from 1 to 5, indicating their importance in the Schiphol environment with additional rationale. The weighted score for criterion i is then computed as:

$$w_i = \frac{r_i}{\sum_{j=1}^{n} r_j} \tag{4.1}$$

where r_i is the rating of criterion i and n is the total number of criteria.

Table 4.3: Weighted Criteria with Rationale

Criteria	Rating	W. Score	Rationale
Flight Accuracy	5	25%	Not only is the flight accuracy highly important for reliable data collection, see Appendix C.1, the flight accuracy also determines the reliability of the drone staying in the constrained airspaces regions whilst in autonomous flight (Chang, Tsai, Lu, & Lai, 2020). An inaccurate drone could lead to operational disasters and thus is rated highest amongst criteria amongst experts, see Appendix E.4.5
Wind Resistance	4	20%	Open airfields often experience strong winds, and a drone lacking sufficient wind resistance can be blown off course or become unstable – a serious safety risk at an airport, with disaster potential (Hristozov & Zlateva, 2018). Assuring wind resistance mitigates this and is thus structurally rated high by expert validation, see Appendix E.4.5.
Water Resistance	3	15%	Airport drones must be water-resistant to operate reliably in rain or wet conditions. Even if drones have a certain threshold, precipitation over time can have an effect of drones, and for a robust integration this is a higher rated criteria (Leng et al., 2015).
Flight Speed	3	15%	Not only is flight speed relevant for potential RCR efficiency improvements, but also for being able to manoeuvrer the drone to a safe home in emergency situations, see Appendix E.3.1.
Battery Life	2	10%	Battery life is important aspect for a drone to complete a full traverse of the runway, as the runway dimensions, see Appendix C.2, allows for identified drones to complete a trajectory, it is rated accordingly
Payload Capacity	2	10%	Drone systems require the ability to carry the MARWIS, see Appendix C.1 and for future modularity a higher payload capacity is seen as beneficial, but not highly relevant for the current comparative analysis.
Operating Temperature	1	5%	With a consistent weather climate in the Netherlands, temperature is not deemed as a crucial criteria for operations, see Appendix D.2 yet prolonged summer weather could impact operation ability and thus should be taken in to account.

To translate each drone specification $x_{k,i}$ per criteria into the discrete 1–5 rating scale $r_{k,i}$, a linear min–max normalization is used following the *Simple Additive Weighting method* (Hwang & Yoon, 1981; Triantaphyllou, 2000). For every criterion i and drone k:

$$x_i^{\min} = \min_k(x_{k,i}), \qquad x_i^{\max} = \max_k(x_{k,i}), \tag{4.2}$$

$$u_{k,i} = \begin{cases} \dfrac{x_{k,i} - x_i^{\min}}{x_i^{\max} - x_i^{\min}}, & \text{if "higher is better,"} \\ \dfrac{x_i^{\max} - x_{k,i}}{x_i^{\max} - x_i^{\min}}, & \text{if "lower is better."} \end{cases} \tag{4.3}$$

$$r_{k,i} = 1 \; + \; 4\, u_{k,i} \tag{4.4}$$

Once the $1 \leq r_{k,i} \leq 5$ ratings are obtained, each drone's overall score S_k is computed by summing across all criteria with weights w_i (from Eq. (4.1)):

$$S_k \; = \; \sum_{i=1}^{n} w_i \, r_{k,i} \tag{4.5}$$

This approach provides a simple and reproducible mapping from raw performance data to the WDM (Olabanji & Mpofu, 2014; Pugh, 1991).

Table 4.4: Weighted Decision Matrix

		DJI Matrice 600 PRO		DJI Matrice 300 RTK		DJI Matrice 350 RTK		Freefly Alta X	
Criteria	**% Score Weight**	**Rating**	**Score Wt.**	**Rating**	**Score Wt.**	**Rating**	**Score Wt.**	**Rating**	**Score Wt.**
Flight Accuracy	25%	1.0	0.25	4.5	1.13	5.0	1.25	5.0	1.25
Wind Resistance	20%	1.0	0.20	5.0	1.00	5.0	1.00	3.0	0.60
Water Resistance	15%	1.0	0.15	5.0	0.75	5.0	0.75	3.0	0.45
Flight Speed	10%	1.0	0.15	5.0	0.75	5.0	0.75	2.6	0.39
Batter Life	10%	1.0	0.10	5.0	0.50	5.0	0.50	4.1	0.41
Payload Capacity	15%	2.1	0.69	1.0	0.15	1.0	0.15	5.00	0.50
Operating Temperature	5%	1.0	0.05	5.0	0.25	5.0	0.25	5.0	0.25
	Total:	–	(1,11)	–	(4.48)	–	(4.60)	–	(3.85)
	Ranking:	–	(4)	–	(3)	–	(1)	–	(2)

The WDM shows that the M350RTK is the best choice of drone according to the criteria specific to the Schiphol Airside.

4.6 Expert Validation

4.6.1 Validation Approach

To validate the criteria, the comparative assessment and the resulting drone system, four expert interviews are conducted. The goal of these interviews is to incorporate real-world expertise into the technical feasibility analysis, ensuring that the subsequent development of the study is realistic, practical and grounded in industry knowledge. To achieve proper validation, interviews are conducted with experts from different sectors in relation to the Schiphol Airport. The various perspectives provide contrasting views on the goal and feasibility of drones for automated use in runway inspections, allowing for a synthesis of opinions. The use of expert interviews as part of this validation process aligns with established guidance for feasibility studies: O'Cathain et al. (2015) emphasise expert interviews play a fundamental role in feasibility research by identifying key uncertainties, surfacing practical challenges, and ensuring contextual fit. This exploratory interview approach enable iterative refinement of technical systems before full-scale implementation and is recommended for complex, real-world settings (O'Cathain et al., 2015). The following four experts have taken part in individual interviews:

Table 4.5: Participants Expert Interviews

ID	Company	Role	Experience (Years)
P1	Royal Schiphol Group	Service Owner Winter Operations and Drones	1-10
P2	Koninklijk Heijmans N.V.	Schiphol CTR Drone Expert	1-10
P3	Helix Aerial Vision	Schiphol CTR Drone Expert	1-10
P4	Samwoh Innovation Center B.V.	Infrastructure Inspection Technical Expert	1-10

The four interviews are conducted according to a semi-structured methodology, assuring the same topics are discussed within each individual interview, whilst also allowing for new topics to be explored, a critical aspect of early-stage research interviews (Kvale & Brinkmann, 2009). As a semi-structured interview involves the same general questions, it allows for a synthesis to be written on converging and diverging views per topic. The expert insights are iteratively incorporated into this chapter, based on this synthesis of their combined perspectives, presented in Appendix E.4.

For detailed information on the interview methodology, including how the experts were approached, the interview setup, and the data collection process, refer to Appendix E.2. For general ethical considerations related to the interviews, refer to Appendix E.1.

4.6.2 Key Takeaways

For a full summary of the expert interviews, refer to Appendix E.

- *Optimal Platform Selection:* Amongst experts, M350RTK emerges unanimously as the most suitable drone for Schiphol RCR operations. This system is deemed to combine state-of-the-art capabilities with modular payload capacity, able to assure flight accuracy, and support MARWIS.
- *Hub Configuration Trade-off:* A dual-hub setup offers rapid redeployment and flexible trajectories, with an expert reporting successful implementations; however, another expert advocates for a single-hub approach to simplify logistics, maximise per-mission data, and reduce operational complexity. It is determined to continue with the dual-hub setup for its potential, and further practical exploration is excluded from the research scope.
- *Sensor Data Integrity:* Low-altitude flight introduce potential interference from propeller downwash—particularly affecting atmospheric data—yet expert consensus holds that careful sensor positioning, proper calibration, and the defined infrared-based measurements substantially mitigate data corruption, urging targeted validation studies, but deeming the setup feasible for the case study.
- *Real-Time Processing Limitations:* Current drone systems lack the real-time analytical throughput and multi-tasking capabilities of current RCR by Kievit, making it unable to completely overhaul the runway inspection procedures; nonetheless, integrated live video feeds point toward a feasible path for future additional tasks such as concurrent FOD detection. It is deemed reasonable to continue the case study objective as a concurrent inspection with other Kievit.
- *Refined Evaluation Criteria:* Flight accuracy and wind resistance are identified as the highest priority criteria for reliable operations, while battery endurance and payload capacity are deemed less of a priority given the length of the runways; these adjusted weightings reinforce the M350RTK superiority without altering the final selection outcome.
- *Weather Resilience Considerations:* Expert drone flight experience indicates the M350RTK can withstand wind speeds beyond its 12 m/s specification, yet it remains more susceptible to adverse weather than a Kievit; bridging this reliability gap will be essential before potentially replacing current inspection methods. For further analysis, 12m/s is kept as a benchmark, but it sheds light on possible specification margins.
- *Overall Feasibility Outlook:* Collectively, the experts agree that drone-based RCR operations at Schiphol are technically feasible but best introduced through a phased adoption. P2/Heij views automated integration as an imminent next step for routine airside tasks—cautioning that specialised applications like asphalt assessment may require further refinement. P4/Si counterbalances this optimism by highlighting the airport's systemic complexities, which have tempered

many early drone promises. In contrast, P3/Hav projects that sustained investment and close collaboration between technology providers and airport operators will ultimately justify efficiency gains. Finally, P1/Sch offers a pragmatic operational perspective: although human oversight remains a legal and functional requirement for airside operations, drones can significantly accelerate data collection protocols whilst working alongside Kievits, particularly on remote runways like the Polderbaan.

4.7 Weather Impact Analysis

This paragraph presents an analysis of weather conditions at Schiphol Airport, assessing the feasibility of the selected drone system in the relevant environment over the past 10 years. A 10-year period was chosen to reflect contemporary weather occurrences influenced by climate change, as The World Meteorological Organization reports that 2011–2020 marked an unprecedented environmental decade (World Meteorological Organization, 2023). Recognizing that drone operations at Schiphol Airport could extend to operation over a full 24-hour period—including night operations—the analysis initially does not restrict itself to specific Schiphol runway inspection times, to assess the complete weather impact. Following this initial weather analysis, specific research is done into wind gusts strictly during airside operational hours.

4.7.1 Aspects Analysed

During the weather analysis, the four aspects are taken in to account, as described in the criteria specification, see Appendix 4.4.2:

1. **Hourly Temperature Data:** temperatures are analysed by reviewing the hourly range that occur during each day and identifying any extreme values that would have exceeded operational performance.
2. **Hourly Precipitation Data:** precipitation is analysed to asses performance during rainfall to understand the frequency and intensity of rainfall events, which impact flight operability.
3. **Hourly Wind Speeds:** wind conditions are examined per hourly interval, focusing on sustained wind speeds that influence the drone's trajectory.
4. **Hourly Wind Gust Speeds:** wind gusts are evaluated by examining highest recorded wind gust per hour, as sudden variations in wind speed can pose additional challenges for maintaining stable flight.

Weather phenomena such as hail, snow, thunder, and other extreme events are excluded from this feasibility analysis due to their low occurrence frequency in the Netherlands, though deemed to be increasing and relevant for future studies (KNMI, n.d.). Visibility range of less than 1000m caused by mist or fog occur on roughly 9% days over the past 10 years, see Appendix D.1. M350RTK is deemed usable in these visibility constraints and prolonged effects of mist and fog on system operability have been left out of this study's scope (DJI, 2023).

4.7.2 Outcomes All Aspects 24-hour (2010-2024)

For the initial 24-hour decadal data analysis, each of the four analysed aspects is plotted in a grid, where each day highlights if that weather aspect allowed a drone flight (green) or not (red). The data analysis reveals that temperature and precipitation both do not pose a threat to functionalities of the M350RTK, as it shows that the temperatures and precipitation at Schiphol Airport consistently fall inside the operational range of the drone. For a data visualisation and margin visualisation of these two metrics see Appendix D.1 and D.1. Table 4.6 gives an overview of the operable days with regard to the four weather aspects.

Table 4.6: Decadal Operability Findings

Metric	# Non-Operable Days	% Operable Days
Hourly Temperature Range	0 out of 3653	100%
Max. Hourly Precipitation Amount	0 out of 3653	100%
Daily Wind Speed Average	29 out of 3653	99.2%
Max. Hourly Wind Speed	211 out of 3653	94.2%
Max Hourly Wind Gust Speed	1312 out of 3653	64.1%
Total	1312 out of 3653	64.1%

The analysis findings show that both average hourly wind speeds and wind gusts pose as hazardous candidates for drone operations at the Airport. Table 4.6 shows the hourly wind would have affected drone flight at an hour in the time in 5.78% per cent of the days over the past 10 years, and in the case of wind gusts even 35.91%. Portrayed in red in Figure 4.3, is the overview of the days that drone flights would not have been operable. It is important to note that wind gusts are sudden and not continuous, meaning that continuous drone operations might have only been made difficult at one point in time, and not over the whole operation day, yet the scope of this part of the analysis is to analyse over a full 24-hour. By assessing Figure 4.4, where margins have been applied, it can be seen that on many days the wind gusts are near the feasibility threshold of the drone's max wind resistance.



Figure 4.3: Daily Max Wind Gust Operability (2014-2024).

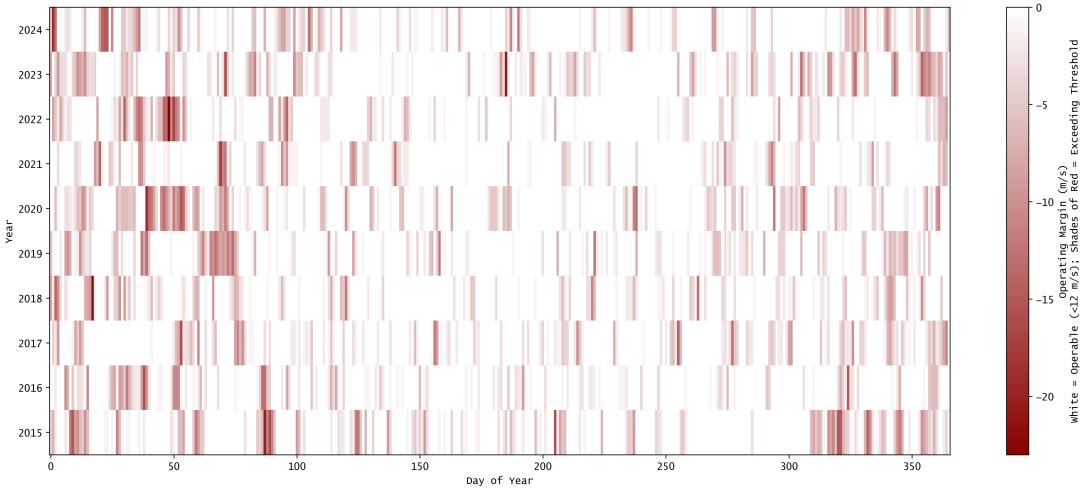


Figure 4.4: Daily Max Wind Gust Threshold (2014-2024).

By employing a sensitivity analysis, it can be seen that the operable days increase significantly with a slight improvement of the drone wind resistance, represented in Table 4.7

Table 4.7: Findings Sensitivity Analysis

Sensitivity %	Threshold (m/s)	Operable Days (%)
2.0	14.0	77.4
1.6	13.6	77.4
1.2	13.2	71.1
0.8	12.8	71.1
0.4	12.4	64.1
0.0	12.0	64.1
-0.4	11.6	55.1
-0.8	11.2	55.1
-1.2	10.8	44.8
-1.6	10.4	44.8
-2.0	10.0	44.8

4.7.3 Outcomes Wind Gust Behaviour 2024

The preceding analysis gives an idea of how often the drone could be operable with regard to wind gusts during a full day, but it's important to realise that a single high gust does not render the drone unfeasible for the entire day. Therefore, as wind gust was deemed to have the most impact, further analysis is done into when within the operational window those gusts occur—so it can be seen, during an otherwise flyable day, at what times the drone is likely to be inoperable. In Figure 4.5, the threshold is visualised at 12 m/s, revealing that the afternoon hours most frequently overshoot the operational limit— with the largest overshoot (21%) exhibited at 14:00.

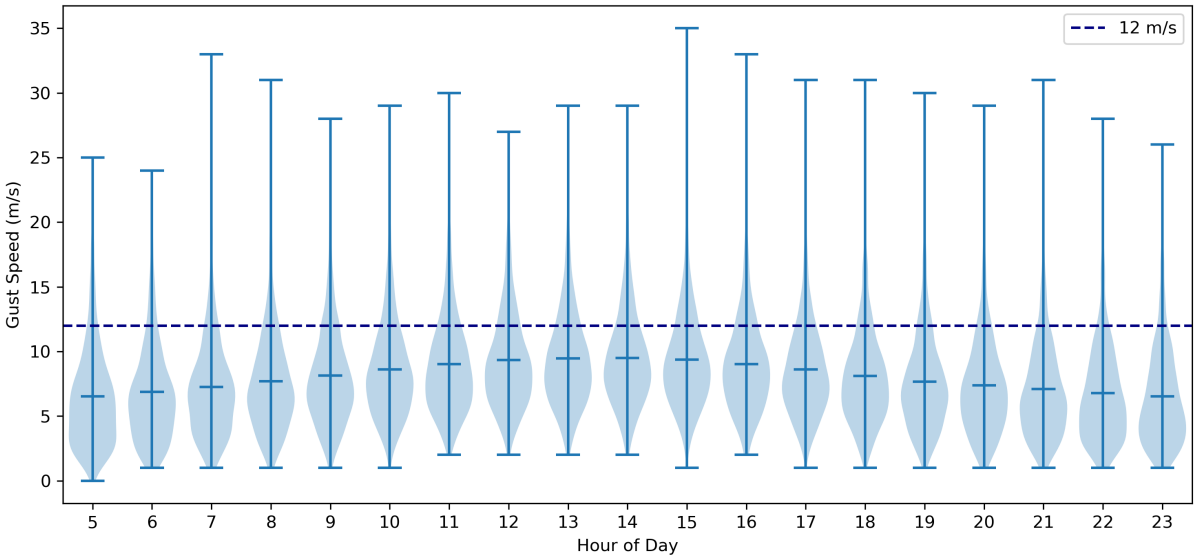


Figure 4.5: Hourly Max Wind Gust Distribution 2024 (05:00-23:00)

The monthly-average profile in Figure 4.6 further reinforces the wind gust trend, showing that gust speeds on average rise steadily into the afternoon across every month. Whilst breaking down the data on *threshold exceeding days* by calendar month, April tops the list with 18 unfeasible days, followed by the winter months January, February, and December. Together, these visuals help in anticipating the feasibility of drones during an operational day and seasons, a critical input for a scheduled autonomous drone integration.

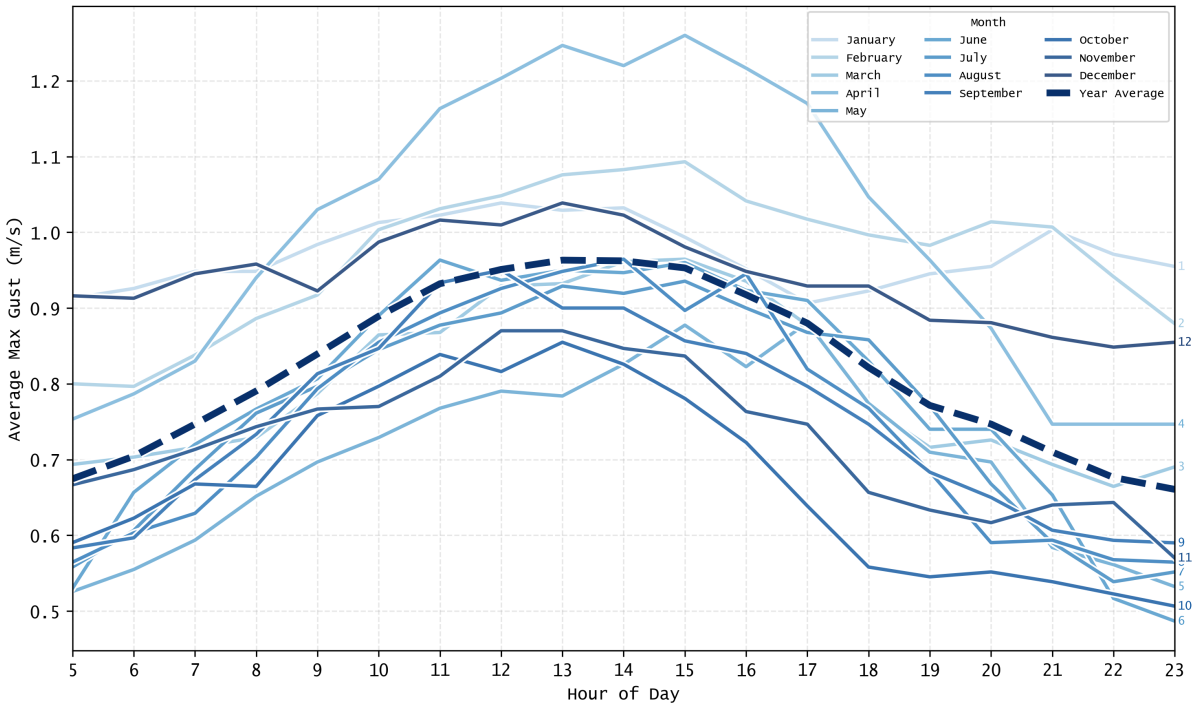


Figure 4.6: Monthly Max Wind Gust Average 2024 (05:00-23:00)

4.8 Drone–Sensor–Hub Interaction

This section describes the technical interaction between drone, payload, hubs and external systems, with the goal of portraying a feasible interaction and technological capabilities, without requiring a thorough understanding of state-of-the-art electronic components outside the scope of this study.

The RCR operation is a closed-cycle routine. Upon mission initialization, the drone departs from Hub A, activates the MARWIS payload, and performs a low-altitude pass along the runway. After completing the inspection, it autonomously lands at Hub B. Data is transferred and forwarded, and the drone is charged for its next mission, with a reversed route.

M350RTK works according to the internal flight controller steering the organisational brain of the drone, the companion computer, which allows for the integration of third-party payloads through the Payload and Onboard Software Development Kits (PSDK & OSDK), providing a digital platform for power, command, and data exchange (DJI, 2023). MARWIS is connected to an onboard module mounted to the payload rail, handling data timestamping using GNSS and Real-time Kinematic (RTK) positioning, according to established drone flight performance as described by Feng and Wang (2008) (DJI, 2023; Lufft GmbH, 2022). A communication framework enables data flow between the drone, docking stations, and Schiphol's data infrastructure. During flight, the drone utilizes its transmission system for real-time command signals (DJI, 2023). RCR involves visual-line-of-sight (VLOS) operations but does fly over long distances thus the system is extended with modules to support communication between the onboard processor and servers housed in the docking stations, see Appendix E.3.1 and I.2. The docking infrastructure consists of two autonomous ground stations positioned at opposing ends of a runway. Each station is equipped with RTK landing support and battery charging systems, serving as autonomous home points for the drone and allowing continuous operations, see Appendix E.3.3. Docking stations explored, but not elaborated on, are compatible with M350RTK (DJI, 2023). Once the drone lands at a hub, a handshake protocol initiates a data sharing E.3.1. Sensor data is transferred to the hub's internal server, which is connected to Schiphol's operational system, where RCR process can finalized.

Figure 4.7 illustrates the mentioned interactions, the drone's internal systems, and the communication framework that supports data handling, and is developed based on state-of-the-art drone systems

designs, inspired by Sihag, Choudhary, Choudhary, and Dragoni (2023).

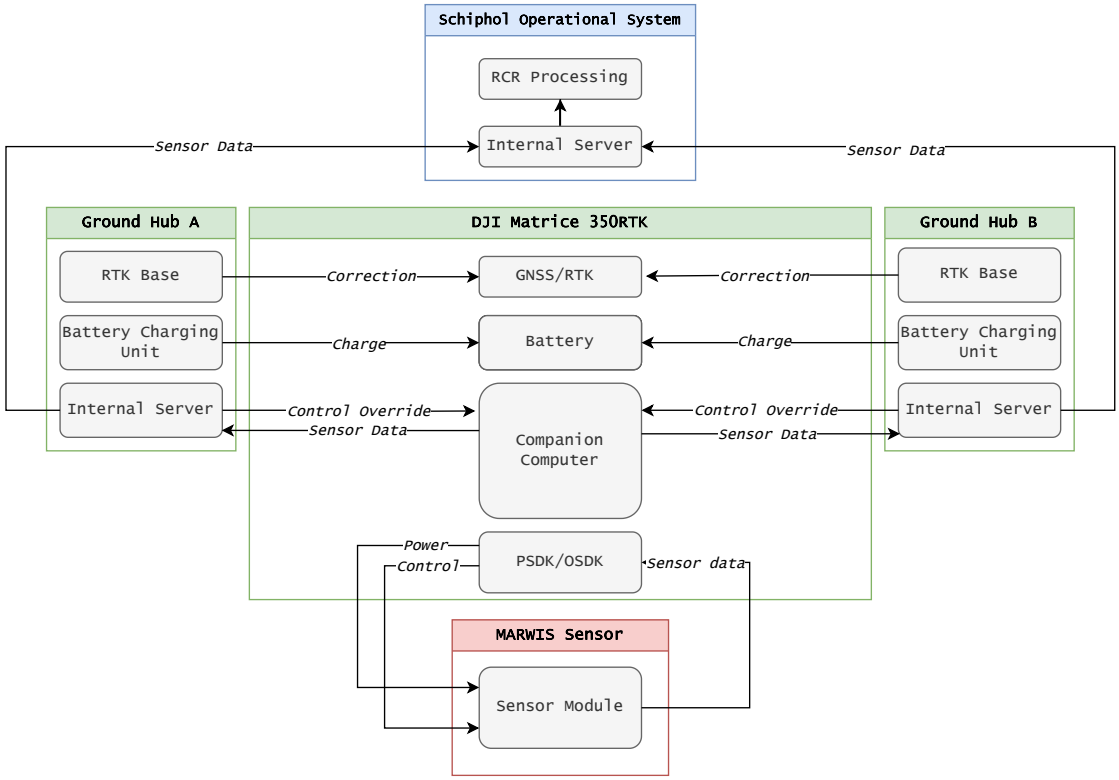


Figure 4.7: Drone-Sensor-Hub Interaction Diagram.

4.9 Chapter Summary

Chapter 4 addressed the question: ***"What technical specifications are required for a drone to reliably perform autonomous runway condition reporting under Schiphol Airport's environmental conditions?"***

Through a feasibility analysis, it was found that there are commercially available drone platforms that meet the operational and environmental demands of autonomous RCR at Schiphol Airport. Criteria were established based on climate data, runway specifications, and sensor requirements, and translated into evaluative metrics. A comparative assessment using a WDM identified M350RTK as the most suitable drone system—primarily due to its superior flight accuracy and weather resistance. This technical selection was validated through interviews with experts from four relevant companies, offering key insights that refined both the assessment criteria and the contextual understanding of drone inspections. Notably, the interviews emphasised that stakeholder alignment is essential for future deployment beyond technical feasibility alone. A weather impact analysis revealed that Schiphol's temperature and precipitation pose minimal operational barriers. However, wind and wind gusts can be limiting: drone operability under gust conditions is reduced to 64% of days, with afternoon hours and winter months being most critical. A sensitivity analysis showed that slight improvements in wind resistance can lead to gains in overall feasibility. Lastly, the system interaction framework between the drone, MARWIS, docking stations, and Schiphol's infrastructure was explored, demonstrating how the technical system of M350RTK could interact with the relevant system components.

The findings of the feasibility analysis show that for the analyzed criteria and environment, autonomous RCR using the M350RTK and MARWIS, is technically feasible within the Schiphol context. This finding forms a validated foundation for the trajectory optimization and risk assessments explored in subsequent chapters.

5 Flight Trajectory Optimisation and Protocol Design

This chapter addresses the steps taken in formulating a flight trajectory and protocol design for RCR by autonomous drones. This is done by determining airside constraints and current protocols by exploring Schiphol and international regulations with a feasible system, determined in Chapter 4.

5.1 Goal & Motivation:

This chapter has two goals: first, to develop an *effective* flight trajectory for the Polderbaan runway at Schiphol Airport, by framing the placement of drone hubs and flight route as an OR problem. In this OR problem, the flight trajectory is minimised for flight time, determined by decision variables adhering to airside constraints. The Polderbaan was chosen because of its relative isolation and straightforward layout, making it an ideal case study for developing a baseline trajectory. As the Polderbaan is farthest away from Schiphol's centre and the most used runway, RCR improvements by drone also have the potential to improve current inspection. This baseline allows for subsequent extension to other runways, by tweaking the decision variables according to runway-specific constraints. The second goal of this chapter is to develop a flight protocol for the optimised trajectory, including the exploration of flight safety procedures in adherence with state-of-the-art drone developments.

5.2 Approach

1. **Trajectory Description:** Initial definition of the intended flight trajectory for RCR.
2. **Operations Research Model:** Formulation of the trajectory optimisation as an OR problem, including objective, decision variables, and constraints.
3. **Trajectory Constraints:** Identification of key constraints shaping the trajectory, such as drone capabilities, runway specifications, and operational considerations.
4. **Hub Placement and Flight Route Design:** Application of the OR model to determine optimal drone hub locations and flight routing based on operational constraints.
5. **Flight Protocol and Safety Procedures:** Development of a accompanying flight protocol including trigger conditions, flight execution, geofenced corridors, integrated emergency responses, and an complete protocol flow diagram.

5.3 Trajectory Description

To perform autonomous RCR, the M350RTK system is tasked with traversing the full length of the Polderbaan runway collecting surface condition data using the MARWIS sensor, see Section 2.2.3. This data forms the core input for three segments of the runway, for the official GRF runway condition report, see Section 2.2.2 (Royal Schiphol Group, 2024c). This linear runway trajectory is preceded and followed by taxiing routes to and from the runway. The complete trajectory consists of three components:

1. **Taxi-In:** Drone departs from Hub A, following a taxiing route to reach the runway start.
2. **Runway Traversal:** Drone flies a linear route along the full length of the runway.

3. **Taxi-Out:** Drone exits the runway end, following a taxiing route to reach Hub B.

An effective trajectory is defined by the drone following the optimised trajectory for departing from Hub A, completing taxi-in, traversing the runway as per the defined flight parameters, and reaching Hub B via the taxi-out route—all while maintaining compliance with regulatory, operational, and technical constraints.

5.4 Operations Research Problem Framing

To optimise the autonomous drone trajectory, as described in Section 5.3, the flight trajectory is framed as a constrained optimisation problem in accordance with the procedures outlined by Carter, Price, and Rabadi (2018). In OR, problems are defined by three components: **Decision variables**—controllable factors that define a solution, **Objective function**—the quantity to be minimised or maximized and **Constraints**—limitations that restrict feasible solutions.

In this case, the objective is to determine the optimal placement of drone hubs and the shortest flight route that minimises total trajectory time, while satisfying operational, safety, and regulatory constraints.

5.4.1 Decision Variables

The primary decision variables in this optimisation model are:

- H_A, H_B: Coordinates of Hub A (departure) and Hub B (arrival)
- $r(t)$: Flight route taken by the drone, including taxiing to and from the runway, and traversing the runway for data collection.
- v_{runway}: Drone velocity during the data collection phase
- v_{taxi}: Drone velocity during taxiing phase
- $v_{\text{asc}}, v_{\text{desc}}$: Drone velocity during ascent and descent phases
- $z(t)$: Drone altitude during flight route

5.4.2 Objective Function

The objective is to minimise the total mission time required to complete RCR, which consists of sequential steps:

1. Ascent from Hub A to trajectory flight altitude — $\frac{z}{v_{\text{asc}}}$
2. Taxiing from Hub A to runway start — $\frac{L_{\text{taxiA}}(H_A)}{v_{\text{taxi}}}$
3. Data collection flight along the runway — $\frac{L_{\text{runway}}}{v_{\text{runway}}}$
4. Taxiing from the runway end to Hub B — $\frac{L_{\text{taxiB}}(H_B)}{v_{\text{taxi}}}$
5. Descent from flight altitude to Hub B — $\frac{z}{v_{\text{desc}}}$

The total mission time T_{total} can thus be expressed as:

$$\min_{H_A, H_B, r(t)} \quad T_{\text{total}} = \frac{z}{v_{\text{asc}}} + \frac{L_{\text{taxiA}}(H_A)}{v_{\text{taxi}}} + \frac{L_{\text{runway}}}{v_{\text{runway}}} + \frac{L_{\text{taxiB}}(H_B)}{v_{\text{taxi}}} + \frac{z}{v_{\text{desc}}} \tag{5.1}$$

5.4.3 Constraints

The optimisation is subject to a range of constraints that affect either the hub placements or flight route:

- **Hub Placement Constraints**: Hubs must be placed outside restricted zones and be accessible for maintenance, see Section 5.5.2, 5.5.3.
- **Flight Route Constraints**: The route must avoid penetrating restricted zones and must not cross active taxiways. The route during data collection must be linear and offset from the runway centreline. Flight route is further constrained for *altitude* and *velocity*, according to system specifications, see Section 5.5.1, 5.5.2.

5.5 Trajectory Constraints

The origin of the described constraints vary. The following section describes the considered constraint from the following origins:

- *Sensor Constraints:* MARWIS sensor usage specifications
- *Drone Constraints:* M350RTK specifications
- *Runway Constraints:* Runway layout, aircraft taxiways and safety zones
- *Operational constraints:* Service roads for autonomous drone and hub operational necessities

5.5.1 Matrice 350RTK and MARWIS Sensor Usability Paramaters

MARWIS has specific operational requirements for *height, speed and flight location*, for full sensor specifications, see Appendix C.1. The sensor can be mounted at three heights 0.5m, 1m and 2m. For optimal performance, a *height of 2 meters* is selected, minimising potential downwind affecting sensor data and flight smoothness, See Appendix E.3.1. The faster the drone moves, the more distance there is between data points, the sensor measures 100 times per second (Lufft GmbH, 2022). The choice of flight velocity thus depends on the required spatial resolution for runway condition reporting. Maintaining a distance of 0.1m to 0.3m between data points is recommended for high accuracy, translating to a speed range of 10 to 30 m/s, see Appendix I.2.

M350RTK specifications are also relevant for flight velocity; M350RTK equipped with MARWIS weighs a total of 8.5kg, resulting in an *estimated* flight time of 40 minutes, and an approximate maximum flight speed of 20 m/s, based on existing payload effects on DJI drones (DJI, 2023, 2025). As this speed exceeds constraints set by MARWIS parameters, the M350RTK specifications constrain the trajectory planning to 20m/s. The ascent and descent of the drone during take-off and landing are respectively constrained to 5 m/s and 6 m/s, as determined by user manual specifications (DJI, 2023).

As MARWIS is designed to measure asphalt conditions, it should not be positioned in the runway centre, as it then would be monitoring the runway centre markings. This constraint thus demands a *off-axis flight route placement*, measuring the asphalt where the wheels of an aircraft would land as advised by the manufacturer (Lufft GmbH, 2022). Additionally for successful RCR using MARWIS, the sensor requires calibration once every three months (Lufft, 2025).

5.5.2 Runway Zones and Feature Considerations

The Polderbaan's autonomous RCR setup requires two fixed docking stations at each end, optimised for a minimal taxing distance before and after runway data collection. Schiphol runways are subject to safety zones determined by international ICAO, European EASA and national IenW regulations (European Union Aviation Safety Agency, 2021; Inspectie Leefomgeving en Transport, 2025; International Civil Aviation Organization, 2017). Four constraint categories are considered to affect flight route and hub placement in the scope of this study: the runway strip and Runway End Safety Area (RESA), the Obstacle Limitation Surfaces (OLS), the ILS areas and the adjacent taxiways.

Runway Strips and Runway End-Safety Area

Runways are surrounded by a two-dimensional runway strip—an area declared to protect an aircraft in case of a veer-off—as well as a RESA intended for over- and undershoots. Their goal is to reduce potential damage if an aircraft runs off the pavement. (International Civil Aviation Organization, 2017). ICAO and EASA standards require the runway strip to extend at least 150m on each side of the runway centreline and at least 60m beyond each runway pavement end for runways with Code 4, meaning they are longer than 1.8km— which all Schiphol runways are (International Civil Aviation Organization, 2017; LVNL, 2024). Within this strip, the surface is kept free of any non-frangible and non-essential obstacles—runway lights, signs, or navigational aids are allowed—to prevent aircraft damage or an aircraft flipping over. Whilst all runway strip distances are 150m on each side, the RESA vary for geographical constraints in adherence with the ICAO protocols and can be found in C.2 (International Civil Aviation Organization, 2017).

Obstacle Limitation Surfaces

Alongside the two-dimensional safety areas—strip and RESA—there are also three-dimensional safety areas. The OLS are segmented areas surrounding the runway strips determining what height obstacles can have per area, as determined by the International Civil Aviation Organization (2017), with the goal to ensure safe universal air flight. As can be seen in Figure 5.1, the OLS has various height allowances per region, accounting for the flight approach and departure areas. The inner red segment, represented by number zero, corresponds with the runway strip and is permitted to host non-essential obstacles. The successive layer, a purple line, represents the area where non-essential objects may have a height of 5m if they are not present in another restrictive zone like RESA or ILS zone. The OLS constrain hub placement, and are relevant for all Schiphol runways, according to Inspectie Leefomgeving en Transport (2025).

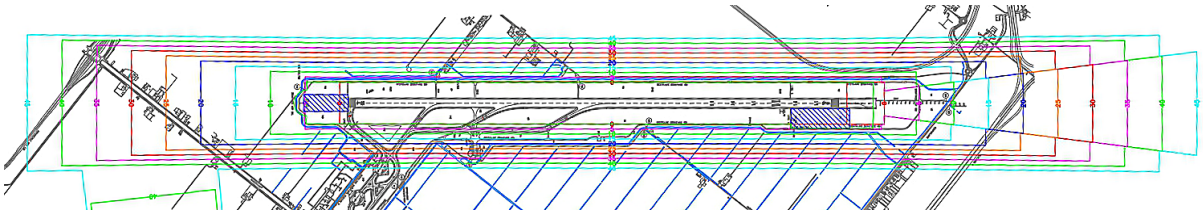


Figure 5.1: OLS Polderbaan (Royal Schiphol Group, 2023), to see enlarged, refer to Appendix F.1

Instrument Landing System Critical and Sensitive Areas

Schiphol's runways are equipped with Category I–III ILS to enable precision aircraft approaches during impaired visibility (International Civil Aviation Organization, 2020). Each ILS consists of a *localizer* antenna for lateral guidance, positioned beyond the departure end of the runway aligned with the centreline, and a *glideslope* antenna for vertical guidance, positioned approximately 300m from the threshold and 120m laterally from the centreline (International Civil Aviation Organization, 2020).

The **ILS Critical Area** is a safety zone around both separate antennas where the presence of transponding entities—aircraft, Kievits, drones—may cause unacceptable interference to the ILS functioning and

affect flight safety. This means their presence is highly restricted whilst the ILS is activated. The ILS critical areas are the blue striped boxes on either side of the runway in Figure 5.1. For the localizer, this area extends *up to 675m in length* and *60m–150m in width*, which is dependent per airport on what aircraft sizes it hosts, determining the antenna placement and range (International Civil Aviation Organization, 2017). The glideslope critical area extends *130m in length* and *up to 60m in width*, positioned directly in front of the antenna array (International Civil Aviation Organization, 2017).

The **ILS Sensitive Area** encompasses the critical area and extends further to protect against minor signal fluctuations during low-visibility operations when ILS is critical for flight safety. For localizer protection, the sensitive area stretches over the end of runway, and adjacent taxiways, covering up to *1,000 meters longitudinally* and *150–300 meters laterally* in the worst weather conditions possible. ICAO guidelines recommend maintaining this area clear when an approaching aircraft is within *2 nautical miles* of the runway threshold (International Civil Aviation Organization, 2017, 2020).

To minimise regulatory risk and ensure operational safety, drone flight routes should be situated *outside the ILS critical areas*, with a minimum buffer distance of 5 meters and hub infrastructure preferably positioned *laterally offset or behind* the localizer and glideslope antennas to avoid interference with the ILS signal path. Even when a runway is not actively in use for arrivals, its ILS components may remain operational or be periodically activated for system testing, calibration, or as part of backup landing configurations. Inadvertent signal distortion—even from small reflective or moving objects—can compromise the integrity of the ILS signal (International Civil Aviation Organization, 2020). Therefore, even if the ILS system is not activated, it still constrains the flight route. In the scope of this study it is assumed that the RCR by autonomous drones will not be taking place in situations where the weather is so dire, that the ILS sensitive areas are activated, thus these area extensions are not a constraint for the flight route or hub placement.

Adjacent Taxiways

Adjacent taxiways may be occupied at any time by aircraft waiting to depart—even before a runway is opened—thus overflying an active taxiway segment with a drone carries unacceptable collision risks, see Appendix I.1. For the Polderbaan, the drone's flight path has been designed to avoid all taxiway crossings entirely. On the other runways, where the taxiway layout makes full avoidance impractical, the drone crosses as little as possible, whilst further practical measures are not described in the scope of the study and the focus on the Polderbaan.

5.5.3 Drone and Hub Operational Considerations

In the assumption that hubs are to be continuously utilized for autonomous RCR, they need to be easily accessible for operational tasks such as maintenance or object clearance. Therefore the operational considerations constrain the placement of the hubs. To satisfy these considerations Hubs are to be placed at a distance less than 5m from airside service roads, whilst not hindering emergency routes.

5.6 Solving the OR-problem: Hub placement and Flight Route

With the objective function, decision variables and constraints defined, this section describes how the solution of the OR problem is found for the hub placement and flight route, to minimise mission time.

5.6.1 Constraint Overview

Table 5.1 summarizes all researched constraints in the scope of the study, and their impact on hub placement and flight route.

Table 5.1: Flight Trajectory Constraints

Aspect	Parameter	Constraint	Source
Hub Placement	Location	Must be placed $\leq$ 5m from airside service road; outside runway strip, RESA, OLS and ILS critical area	Runway Constraint (Sect. 5.5.2); Operational Constraint (Sect. 5.5.3)
	Height	Docking-station structure must be $\leq$ 5m according to OLS to be placed as close to the runway as possible.	Runway Constraint (Sect. 5.5.2)
Flight Route	Speed	Flight speed is constrained to $\leq$ 30 m/s for accurate sensor data collection by MARWIS usability, and further constrained to 20 m/s by maximum velocity by drone specifications carrying a payload. Ascent and Descent during Taxiing respectively constrained to $\leq$ 6 m/s and $\leq$ 5 m/s by drone.	Sensor Constraint (Sect. 5.5.1); Drone Constraint (Sect. 5.5.1)
	Height	2m above runway surface as constrained by MARWIS usability, can not fly lower due to increased down-wash effect by Drone usability.	Sensor Constraint (Sect. 5.5.1); Drone Constraint (Sect. 5.5.1)
	Location	Linear off-axis path along aircraft wheel tracks; avoid centre-line markings; remain outside runway strip, RESA and ILS. A buffer region of 50m of ILS is determined. Taxi path must avoid aircraft taxi lanes.	Sensor Constraint (Sect. 5.5.1); Runway Constraint (Sect. 5.5.2)

5.6.2 Problem Solution

Before applying the constraints, the total mission time T_{total} is expressed as:

$$T_{\text{total}} = \frac{z}{v_{\text{asc}}} + \frac{L_{\text{taxiA}}(H_A)}{v_{\text{taxi}}} + \frac{L_{\text{runway}}}{v_{\text{runway}}} + \frac{L_{\text{taxiB}}(H_B)}{v_{\text{taxi}}} + \frac{z}{v_{\text{desc}}} \tag{5.2}$$

Applying the known system constraints step-by-step reduces the number of decision variables:

- The flight altitude z is constrained to a constant value of 2 m. (Drone and Sensor Constraint, Sect. 5.5.1)
- The ascent speed v_{asc} is maximized, and thus constrained to 6 m/s (Drone constraint, Sect. 5.5.1).
- The descent speed v_{desc} is maximized and thus constrained to 5 m/s. (Drone constraint, Sect. 5.5.1)
- The data collection speed v_{runway} is maximized and thus constrained to 20 m/s (Drone Constraint, Sect. 5.5.1)
- The taxi speed v_{taxi} is also fixed at 20 m/s (Drone Constraint, Sect. 5.5.1).
- The runway length L_{runway} is known for each runway. For the Polderbaan, the part which is to be inspected is 3700 m. of the total length of 38– m (Runway Constraint, Sect. 5.5.2)
- $L_{\text{taxiA}}(H_A)$ and $L_{\text{taxiA}}(H_A)$ are yet to be optimised with the simplified objective function.

Substituting the described constraints into the objective function yields:

$$T_{\text{total}} = \frac{2}{6} + \frac{L_{\text{taxiA}}(H_A)}{20} + \frac{3700}{20} + \frac{L_{\text{taxiB}}(H_B)}{20} + \frac{2}{5} \tag{5.3}$$

$$T_{\text{total}} = 0.333 + \frac{L_{\text{taxiA}}(H_A)}{20} + 185 + \frac{L_{\text{taxiB}}(H_B)}{20} + 0.4 \tag{5.4}$$

$$T_{\text{total}} = \left(\frac{L_{\text{taxiA}}(H_A) + L_{\text{taxiB}}(H_B)}{20} \right) + 185.733\,\text{s} \tag{5.5}$$

This formula accounts for the time spent ascending, descending and traversing the runway. Therefore what is left to minimise total mission time, is minimising the taxiing distances from and to the hubs:

$$\min_{H_A, H_B} \quad L_{\text{taxiA}}(H_A) + L_{\text{taxiB}}(H_B) \tag{5.6}$$

Hub Placement and Route Determination

To determine the optimal hub positions and drone flight route for the Polderbaan, a staged spatial analysis is conducted: first placing the two hubs, and then determining the taxi routes to and from the runway start and end.

- **Hub A Placement:** Hub A, located on the left side of the runway, was required to be positioned outside the RESA and ILS critical zones (Runway Constraint, Sect. 5.5.2) and within 5 m of an airside service road (Operational Constraint, Sect. 5.5.3). Two feasible areas were identified using high-resolution satellite imagery and regulatory maps: one to the immediate left of the runway (Option 1) and one below it (Option 2). Although Option 2 offers a shorter taxiing distance, it would require the drone to cross an aircraft taxiway (Runway Constraint, Sect. 5.5.2). Therefore, Option A was selected.
- **Hub B Placement:** Similar analysis was applied for Hub B on the right side of the runway. Two potential areas were identified: one directly east of the runway end (Option 1) and another slightly southeast (Option 2). Since Option 2 is not obstructed by taxiways and provides a shorter taxi distance, it was chosen as the optimal placement.
- **Flight Route from Hub A to Runway Start:** With the hub locations fixed, the taxiing route from Hub A to the runway entry point was designed to avoid ILS critical and buffer zones (Runway Constraint, Sect. 5.5.2). The trajectory circumvents the rectangular ILS critical zone by following its perimeter before reaching the runway starting position.
- **Flight Route from Runway End to Hub B:** The return route from the runway end to Hub B is unconstrained by ILS critical zone or aircraft taxiways, allowing for a direct, linear path.

Polderbaan Trajectory Result

Based on the constraints and optimisation process described, the following trajectory configuration resulted for the Polderbaan. Additional trajectory configurations for Schiphol's other five runways are included in Appendix G.

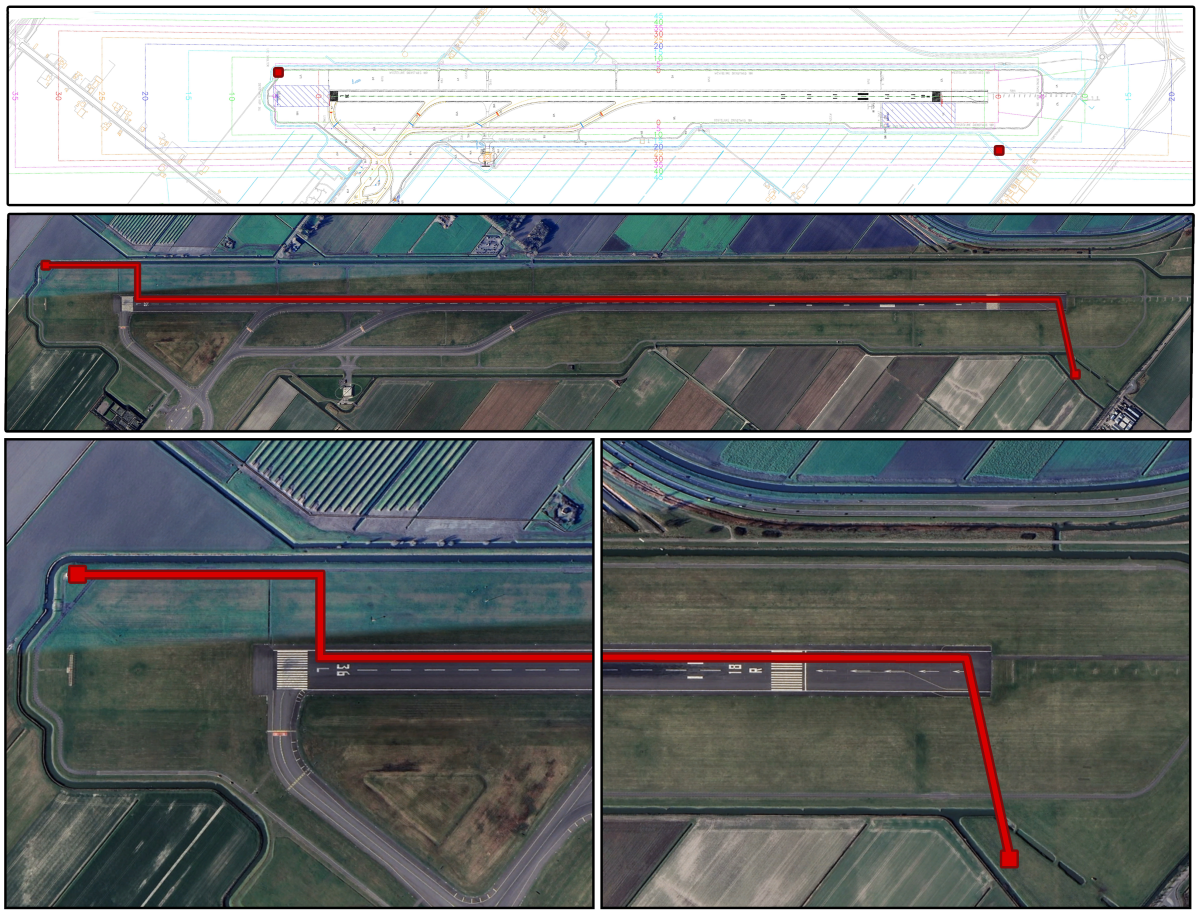


Figure 5.2: Hub Placement and Flight Route Polderbaan (Google LLC, 2025; Royal Schiphol Group, 2023)

Using the finalized hub positions and flight route, the specific distances for the segments were measured for

- $L_{\text{taxiA}} = 480\,\text{m}$ — from Hub A to the runway start
- $L_{\text{taxiB}} = 230\,\text{m}$ — from the runway end to Hub B

Substituting these values into the simplified objective function:

$$T_{\text{total}} = \left(\frac{L_{\text{taxiA}}(H_A) + L_{\text{taxiB}}(H_B)}{20} \right) + 185.733\,\text{s}$$

$$T_{\text{total}} = \left(\frac{480 + 230}{20} \right) + 185.7 = \left(\frac{710}{20} \right) + 185.7 = 35.5 + 185.7 = \mathbf{221.2}\ \text{s}$$

This yields a total mission time of approximately **221 seconds**, or **3 minutes and 41 seconds**, which includes ascent, runway traversal, taxiing, and descent. Given all spatial, operational, and technical constraints, this configuration represents the most time-efficient regulation-compliant trajectory for autonomous RCR by drone at the Polderbaan.

5.7 Flight Protocol

The designed flight trajectory operates within a flight protocol that governs when it is executed, the various phases of the flight, what safety procedures are involved and when they are triggered. The complete protocol flow is visualized in Figure 5.5.

To enable practical implementation, adjustments to existing runway inspection procedures and drone flight policies are necessary. While the current procedures outlined by Royal Schiphol Group (2024c) have been taken into account during protocol development, effective deployment in real-world operations requires modifications to both inspection workflows and airspace regulations. These required adjustments are further discussed in Section 10.2.

5.7.1 Trajectory Trigger and Execution

RCR operational trigger for the autonomous drone is determined to be equivalent to the current operational trigger for a Kievit runway inspection, see in Section 2.2.1. The drone trajectory executes when a runway opening is requested by LVNL, and initiated by FMA. Currently, this involves the Kievit having to travel to the runway start from its idle location, which can vary. As drone hubs are placed strategically, RCR has the potential to be finalized before a Kievit arrives.

Drone flights consist of several distinct stages, as outlined in the literature by Hussein et al. (2021). These stages include taxiing, take-off, climb, cruise, descent, and landing, each with specific parameters, objectives, and execution steps. In the case of this study, these stages are grouped into three operational phases tailored to autonomous RCR. As illustrated in Figure 5.3, each phase integrates multiple flight stages to match the specific trajectory requirements while remaining consistent with the framework proposed by Hussein et al. (2021).

Phase 1 and 3 include take-off, ascent, descent, and taxiing to and from the data collection start point. As the determined flight route for the Polderbaan does not intersect with any aircraft taxiways, the drone maintains a constant flight altitude of 2 meters throughout the entire trajectory. During all phases, the flight speed is constrained by the drone's payload weight, as detailed in Table 5.1, and is fixed at 20m/s.

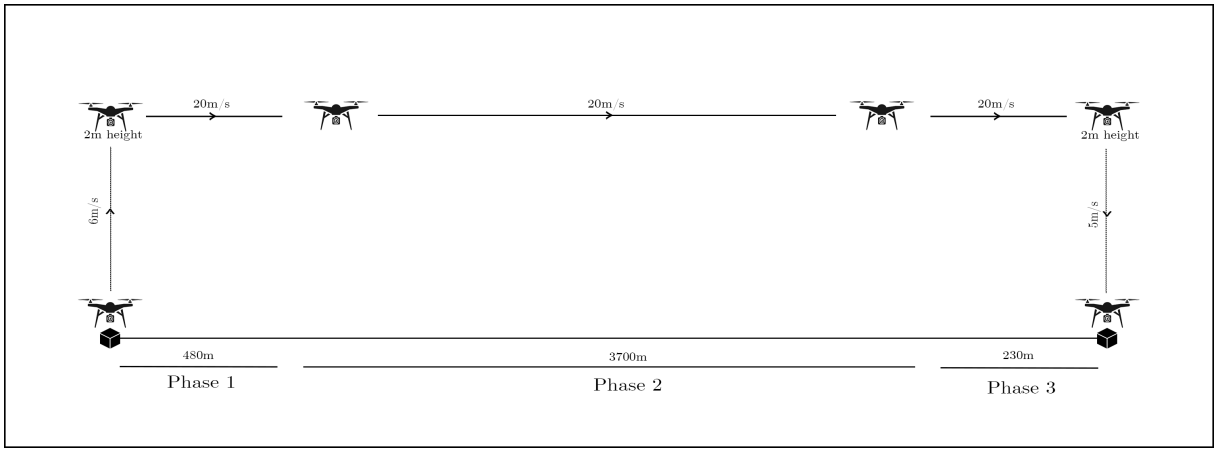


Figure 5.3: Flight Execution Polderbaan

5.7.2 Flight Safety Procedures

Safety during the autonomous drone trajectory in the airside environment is approached through a combination of onboard systems and trajectory-specific emergency procedures. State-of-the-art technologies such as a CAS, enable the M350RTK to proactively avoid obstacles and maintain flight stability, see Section 5.7.2 for a detailed overview. However, to ensure safety in case of unexpected failures or deviations, additional safety procedures are described. These include an automated RTH procedure

and EL procedure, both triggered by geofence violations or critical failures described in this subsection. Together, these measures can be described as a double redundant procedure, and ensure that the drone remains within a tightly controlled flight corridor and can respond autonomously to potential risks, aligning with established research and best practices for safety in complex environments (Szabolcsi, 2016).

Adhering to State of the Art Drone Flight Safety

The M350RTK system comes with onboard safety systems that align with the safety advancements of drone systems discussed in Section 2.4. M350RTK specific CAS uses forward, backward and downward vision sensors plus time-of-flight detectors to detect and autonomously avoid obstacles in real time (DJI, 2023). Functionalities such as DJI AirSense, provide traffic alerts for nearby aircraft and can adjust a flight path to prevent airspace conflicts that may arise (DJI, 2023). Internally, the flight controller can enable automatic switchover on sensor failure to maintain stable attitude and position control (DJI, 2023). Further, anti–jamming and anti–spoofing algorithms monitor signal integrity, with M350RTK having the ability to switch to Vision Positioning System when interferences are detected, ensuring accurate localization without GPS (DJI, 2023). These layered safeguards remain active throughout all flight phases, see Section 5.7.1, preventing conflicts with aircraft, ground vehicles, and infrastructure. The M350RTK works with RTH and EL procedures and is consistently described during expert interviews as a safe and usable system for airside, see Appendix E.4 and Appendix I.2.

Return-to-Home Procedure

RTH procedure is a safety feature that is triggered under various conditions including but not limited to; loss of communication or control link failure, battery failure, critical system malfunctions or deviations from the assigned flight corridor (DJI, 2023). When activated, the RTH procedure guides the drone back to one of two predetermined hubs positioned outside of critical airspace, reducing further risks or operational disruptions (DJI, 2023). A recommended RTH altitude, is a 30 meter height, able to clear grounded aircraft on airside, see Appendix E.3.1.

Emergency Landing Procedure

The EL procedure is a safety feature designed to activate when a critical failure is detected when a RTH fails or when the drone breaches the defined geofence. In such cases, the drone immediately halts its movement and transitions into a hover, following established safety protocols as described by Farajijalal, Eslamiat, Avineni, Hettel, and Lindsay (2025). Once the system confirms that the area directly beneath the drone is free of obstacles, it initiates a controlled vertical descent using its onboard sensor suite for guidance. This method ensures that, even under partial system failure, the drone can autonomously execute a safe landing (Farajijalal et al., 2025).

5.7.3 Drone Flight Corridors and Geofencing

Drone flight corridors are predetermined paths that guide the drone within designated safe zones, surrounding this corridor are geofences preventing drone interference with uncleared airspace that might host aircraft, ground vehicles, or critical infrastructure, a common practice in high-risk areas (Boselli et al., 2017; Kim & Atkins, 2022). In the context of autonomous drone trajectories for RCR the geofences provide an obstruction-free corridor for all phases of the trajectory.

M350RTK integrates geofencing features that allow the definition of three-dimensional boundary around the intended flight path, following academic examples as by DJI (2023); Kim and Atkins (2022). If the drone approaches a boundary, a built-in system trigger initiates the RTH procedure, see Section 5.7.2. In effect, geofencing acts as a "digital leash" that actively contains the drone within its intended flight corridor.

For the specific case of the Polderbaan at Schiphol, geofencing and flight corridors are tailored to the designed trajectory, taking into account the airside environment and drawing on academic research

into airport geofencing as described by Torens, Nikodem, Dauer, Schirmer, and Dittrich (2020) and Kim and Atkins (2022). The Geofence consists of a horizontal and a vertical dimension:

- **Horizontal Dimensions:** A multilayer geofencing scheme is applied, segmenting the airspace into three risk zones:
  - **Green Zone (Flight Geography):** Covers the runway segment observed during Phase 2, as well as the taxi route to and from the runway. This zone defines what would be the approved airspace in which the drone is would be allowed to operate.
  - **Orange Zone (Contingency Area):** A 10 m buffer zone surrounding the Green Zone. If the drone would enter this area, the RTH procedure is automatically triggered. This buffer also applies along the taxi route.
  - **Red Zone (Emergency Area):** Marks the outer boundary of acceptable operation. If the drone would breach this zone, it indicates a total loss of containment. This immediately triggers the EL procedure, forcing a controlled emergency landing to prevent entry into high-risk areas, such as nearby take-off or climb-out corridors (Torens et al., 2020).
- **Vertical Dimensions:** The vertical flight geofence is centred around the fixed execution height of 2 m, with a 10% buffer zone to allow for minor deviations, in which MARWIS is still usable. Heights between 2.2 m and 30 m define the vertical contingency area and are reserved for RTH manoeuvrers. Altitudes above 30 m are designated as emergency space, and entering this range triggers the EL procedure.



Figure 5.4: Geofence Polderbaan (Google LLC, 2025)

5.7.4 Flight Protocol Flow

To summarize the flight trajectory execution and associated safety procedures, the complete operational protocol is visualized in the workflow diagram, see Figure 5.5. In this overview the geofence zones logic has only been visualized for phase 2.

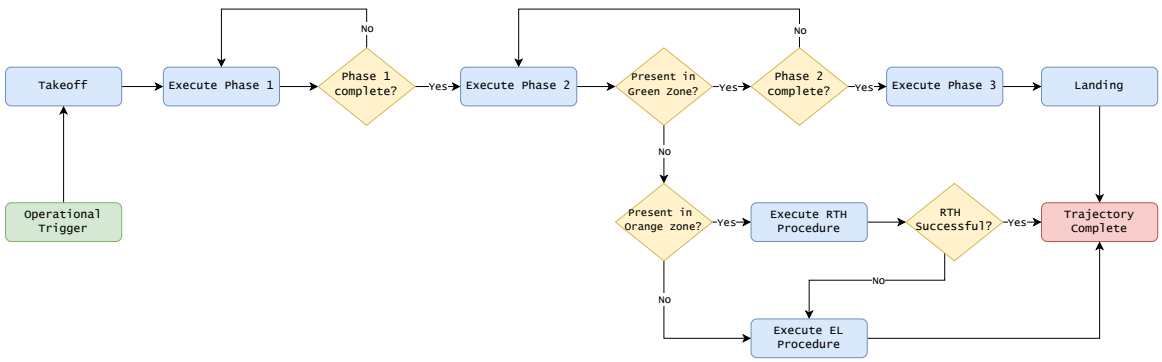


Figure 5.5: Flight Protocol Flowchart

5.8 Chapter Summary

This chapter addressed the question: ***"What specific autonomous flight trajectories and operational protocols are required to effectively perform runway condition reporting at Schiphol Airport?"***

The approach involved translating the feasible drone system capabilities, defined in Chapter 4, into an airside-compliant flight trajectory and operational protocol, focused on the Polderbaan as a use case. An OR problem framing was utilized to optimise the flight trajectory, analysing the constraints of Schiphol airside, and identifying the spatial, regulatory, and system-specific limitations that shape both hub placement and drone flight routes. Critical factors include the ILS areas, which define prohibited airspace for drones, and the OLS limitations and service roads, which influence hub infrastructure placement. The resulting solution minimised the total mission time by optimising hub locations and route segments under the defined constraints. The finalized trajectory for the Polderbaan yields a mission time of **3 minutes and 41 seconds**, including ascent, data collection, taxiing, and descent. Building on this, a flight protocol was designed. The protocol includes phase-specific flight planning, operational triggers, and safety procedures. A safety system is proposed incorporating state-of-the-art onboard technologies, geofencing, and double redundant emergency procedures: RTH and EL. Together, these provide a robust operational safety framework tailored to the airside environment.

In summary, within the defined scope and assumptions of this case study, this chapter presents an optimised flight trajectory for autonomous RCR at the Polderbaan, supplemented by an operational protocol and safety procedure. Findings are essential prerequisites for the subsequent HAZOP analysis and risk assessment.

6 Risk Assessment

This chapter concerns the assessment of risks involved with the developed trajectory for RCR described in chapter 5, for the autonomous drone system deemed technically feasible in Chapter, 4. This is done by applying a HAZOP study to systematically identify process deviations, their causes and their consequences. This risk assessment, with at its core a safety meeting with identified Schiphol stakeholders, involves an evaluation of the HAZOP identified risks with regards to probability and severity. The focus is specifically on the Polderbaan trajectory, mirroring the scope defined in Chapter 5.

6.1 Goal & Motivation:

The goal of the assessment is to gain an understanding of the risks involved with executing autonomous drone RCR at the airside of Schiphol. This approach aligns with the objective intention of HAZOP as described by Rausand (2011): *"identifying deviations from intended process execution and designing safe protocols to prevent resulting consequences"*. In the scope of the assessment, the focus is the optimised RCR trajectory at the Polderbaan: the HAZOP examines possible procedure deviations per phase, described in Section 5, the root causes, consequences, and how they affect the runway inspection. The purpose is not to dissect a drone's internal components and prompt a redesign but rather to analyse possible failures during RCR and its effects on the environment in which it operates. Understanding the risks of an autonomous drone not operating according to protocol is crucial for eventual adoption, thus this assessment plays a role in the early stages of its development.

A key motivation for this risk assessment to use a HAZOP study, is its ability to provide stakeholders with an understanding of the system design, aided by the evaluation of risks using scores and matrixes. A HAZOP allows for discussion with regards to probability and severity, as well as brainstorming safeguards and actionable protocols, in this study necessary for the innovations development. (Muram & Javed, 2021; Rausand, 2011). HAZOP is a well-documented analysis, deemed a good match for the developed trajectory design, as the technique is known to yield beneficial conclusions when carried as early in a system design, resulting in potential process improvements. It is also acknowledged, that for a HAZOP you need, you need a near complete concept, to which the trajectory design provided (Rausand, 2011). Using this risk assessment technique, iterative improvements can be made to the trajectory design, utilizing HAZOP benefits for the wider goal of the casestudy.

Whilst initially developed for analysing chemical process systems, 60 years of evolution has positioned HAZOP as useful in all kinds of complex operations (Rausand, 2011). Although no HAZOP study exists into the use of drones for runway inspections, existing research does examine drone intrusions in high-risk environments. As an operationally malfunctioning drone can be seen as similar to an intrusive drone, this study aligns with learned lessons from risk assessments in academic literature by Pascarella et al. (2022). HAZOP has also been used in drone-based and autonomous systems, for identifying safety and security issues in the design and development phases (Muram & Javed, 2021). A more broad HAZOP analysis of general drone uses in military tasks has also been reviewed by Basavaraju et al. (2019) and has been successfully applied in analysing the process of aircraft inspections with drones, of which lessons have been learned for the application in this study (Hikmet Karakoc et al., 2021).

6.2 Approach

- **Methodology:** Outlines the step-by-step execution of the HAZOP, including procedural steps, success criteria, potential pitfalls, and trajectory segmentation.
- **Team Setup:** Details the multidisciplinary composition of the HAZOP team, specifying participant roles and departmental affiliations.
- **Results:** Summarizes key findings from the safety meeting, highlighting high-severity risks, root causes, potential consequences, and proposed mitigations.
- **Limitations:** Discusses the methodological and contextual limitations of the risk assessment and their potential influence on outcomes.
- **Review Meetings:** Describes the follow-up sessions held to evaluate and refine the initial HAZOP conclusions in collaboration with stakeholders.

6.3 Methodology

HAZOP guidelines describe various types of analysis approaches, this study adopts *the process HAZOP approach*: fitting for system operability and hazards relevant to the implementation of drones for RCR. This method uses process operation nodes, whilst not focussing on the human-machine interaction aspects for which a *procedure HAZOP* is more applicable (Rausand, 2011). The strength of a process HAZOP lies in analysing a process according to hazards and operability in a multidisciplinary team; combining personal expertise and operational experience to dissect a process, not only unearthing consequence hazards but also agreeing on necessary safeguards and protocol steps (Rausand, 2011). This team-based analysis has been shown to lead to more robust processes using co-validated outcomes (Crawley, Preston, & Tyler, 2008).

The HAZOP methodology is according to risk analysis techniques described by Rausand (2011) and is based on the critical examination technique and subsequently, guidelines developed by the Chemical Industries Association by Rausand (2011) with structured implementation and exemplary set up described by Cheraghi, Baladeh, and Khakzad (2018). Since then, HAZOP has often been adapted to other systems outside the chemical industry, this study fits in the more modern adaptions of the developed methodology described in "HAZOP: Guide to Best Practices" by Crawley et al. (2008). Additionally, this study methodology is developed by analysing adaptions of these guidelines to drone systems HAZOP as found in academic literature.

This analysis incorporates several adaptations to the classical worksheet format to reflect the appropriate setting of autonomous drone operations at Schiphol. In a traditional HAZOP, *"actions recommended"* and *"action allocated to"* columns are populated with well-established safeguards and clearly defined responsible parties; according to the guideline it is then decided on, during the HAZOP meeting, who takes what actions to implement safeguards, with follow up meetings to track if the task is completed. However, the absence of any prior autonomous-drone protocol at Schiphol made such assignments inherently ambiguous. Accordingly, *action allocated to* was interpreted as the party responsible for mitigating and following up on the identified consequences of system deviations in the operational environment, with their action being recorded in the *action recommended* column. Additionally, the probability and severity metrics were added to the worksheets for direct evaluation.

6.3.1 Procedure steps

A HAZOP procedure starts by dividing the system to be analysed into sections. This study segments the RCR trajectory according to three flight phases determined in Section 5.7.1, to manage complexity and single out potential hazards (Rausand, 2011). For each phase, process nodes are described, each with a design intent describing how that node is supposed to function. Subsequently, for each node, parameters are determined: variables like velocity or altitude that capture the essence of the node's operation. During the HAZOP safety meeting, each parameter is examined in turn by applying a guideword, chosen according to the guidelines by Crawley et al. (2008) and can be found in Appendix

H.1, to assess potential deviations from the design intent. This set-up is noted in *worksheets* prepared before the safety meeting, and is based on examples by Rausand (2011) and Crawley et al. (2008).

For each identified deviation, a multidisciplinary team investigates possible causes and evaluates their consequences. Based on that analysis, team members recommend specific consequence-mitigating actions and responsibilities. All findings are recorded systematically on the HAZOP worksheets. This process is repeated for each node in each phase until every parameter is accompanied by a guideword and additional information. As a thorough assessment of each node is not possible in the 2.5 h time frame of a safety meeting, additional pre and post-processing is done for parameter deviations deemed logical or extend logic determined earlier in the meeting.

6.3.2 Succes Criteria and Potential Pitfalls

The success of this HAZOP rests on four interdependent pillars described by Rausand (2011). First, it requires *"proper process description and system data"*, described respectively in Chapter 4 and Chapter 5 to ensure every deviation, cause and consequence is grounded in the system definition. To be able to do this properly Rausand (2011) has described necessary prerequisites which can be seen in Appendix H.1, satisfied by the components of preceding chapters. Second, it demands preparatory steps—clear agendas, precisely worded design intents and ready-to-use worksheets—to steer a short and focused safety meeting. Third, a selection of team members with specific expertise should guarantee that discussion inputs are practical and informed. Fourth, the group must exercise proportionality when judging risk severity, avoiding both escalation of risk evaluation.

At the same time, several well-known pitfalls must be actively countered: diving too deeply into specifics of a hazard, allowing scope creep to derail the agenda, permitting bias to colour outcomes, or creating defensive opinions as though under audit (Rausand, 2011). To prevent this, meetings are limited to 20 minutes per phase, the agenda is locked to the predefined scope and team members are reminded that the exercise is a collaborative effort. All members have taken place in such a safety meeting before. By embedding these measures up front, the HAZOP aims to surface actionable hazards and operability issues, whilst trying to evade unnecessary complexity. See Appendix H.2 for further safety meeting set-up.

6.3.3 Trajectory Segmentation

The trajectory system is segmented in to three phases, as mentioned in Section 5.7.1, as the following.

Table 6.1: HAZOP Phases, Nodes and Parameters

Phase	Node	Parameters
[P1] Pre-Mission	[N1] Pre-Launch Check	Battery Charge, Sensor Ready, GPS lock
	[N2] Launch Execution	Mission Trigger
	[N3] Taxiing Execution	Altitude, Arrival Location
[P2] Mission	[N4] Flight Execution	Altitude, Velocity, Horizontal Positioning, Battery Charge, Free Airspace
	[N5] Data Collection	Sensor Calibration, Measurement Rate, Data Quality, Geotagging Accuracy
	[N6] Communcation and Control	Signal Strength, Control Integrity
	[N7] Emergency RTH	RTH Trigger, Navigation Path, RTH Altitude
	[N8] Emergency Landing	Emergency Landing Trigger, Descent Speed, Shutdown Sequence
[P3] Post-Mission	[N9] Post-Flight Docking	Docking Alignment, Power Transfer, Data Offload, Shutdown Sequence

6.4 Team Setup

In a classic HAZOP there are multiple roles, in this adaption, the team leader and secretary roles are combined. The roles and responsibilities are based on guidelines by Rausand (2011).

HAZOP Team Leader and Secretary: Defining scope for the analysis, selecting HAZOP team members, planning and preparing safety and review meetings. The team leader triggers the discussion using guide words and parameters and then follows up on progress to ensure completeness of the analysis. As secretary of the HAZOP process, the team leader prepares HAZOP worksheets, records the discussion in HAZOP meetings and prepares draft reports. The team leader is preferred to be independent of the core organisation, as this safety meeting is led by an independent intern writing a thesis for the TU Delft at Schiphol this requirement is satisfied to a certain degree.

HAZOP Team members: The team consists of multidisciplinary members with a responsible function in the Schiphol Airport environment, from various companies all identified as key stakeholders with high-power and high-impact in Section 4.3

Table 6.2: Participants HAZOP Safety Meeting

Participant	Company	Role	Experience (Years)
P1	Royal Schiphol Group	Safety Advisor	> 25
P2	Royal Schiphol Group	Sr. Safety Advisor	> 25
P3	Royal Schiphol Group (FMA)	Flow Manager Aircraft	> 25
P4	Royal Schiphol Group (APM)	Service Owner Aircraft	1–10
P5	Luchtverkeersleiding Nederland (LVNL)	Operational Risk Manager	1–10

The team was formed in collaboration with the **Safety Department of Royal Schiphol Group.** Together a HAZOP meeting was set up in accordance with HAZOP guidelines as well as Schiphol safety meeting standards, see Section H.2

6.5 Results

6.5.1 Key Takeaways Safety Meeting

For a full summary of the safety meeting, held on 22-05-2025, see Appendix I.1

- *Collaborative Consensus:* The safety meeting enabled stakeholders to agree and disagree on proposed drone trajectory phases and develop a shared understanding of its associated risks. This iterative process not only refined the trajectory design in real time but also raised awareness among key stakeholders of future integration potential of autonomous drones at airside and how this could affect their individual work-field.
- *Rerouted Taxi Path:* The taxi route was reevaluated to follow a longer perimeter path, around the ILS instead of crossing directly over the taxi route due to the potential of idled aircraft before a runway opening, reducing the risk of aircraft collision and enhancing overall integration safety.
- *Established Unified Probability and Severity Scales:* The team collaboratively defined quantitative probability and severity ratings, which were applied during and after the meeting to each identified parameter deviation, allowing a consistent framework to ground the risk assessment and ensuring informed decision-making during and after the meeting.
- *GPS Jamming and Spoofing as Critical Deviation Drivers:* The team identified intentional and accidental GPS signal jamming and spoofing as critical threats to control integrity and something the airport is already managing, underscoring the need for further development of anti-interference measures and redundant navigation safeguards for autonomous drone integration.

- *Geofence Integrity and Failsafe Redundancy:* Defined geofences were deemed essential for maintaining the drone within approved airspace. Failsafe protocols—RTH and EL sequences—were discussed to provide double redundancy and mitigate high-risk consequences. However, as prompted by safety advisors, if both procedures fail, risk severity increases dramatically, underscoring the need for thorough validation of safeguards before further operational development.

6.5.2 Determined Evaluation Metrics

The majority of the process node deviations were discussed in the safety meeting for their probability and severity to the operational airside if occurred. The deviations were evaluated live with the determined metrics in Table 6.3 and 6.4. Both probability and severity keyword and quantification are based on Basavaraju et al. (2019), and tailored to this study with regards to descriptions and occurrence. The tailoring was done in coherence with the complete team during the safety meeting, forming a co-validated ranking for the identified risks.

Table 6.3: Safety Risk Occurrence Probability

Keyword	Level	Description	Occurrence (per flight)
Frequent	5	Likely to occur often in an operational year.	$p \geq 1$ in 10
Probable	4	Likely to occur several times in an operational year.	1 in 100 $\geq p \geq$ 1 in 10
Occasional	3	Possible to occur sometime in an operational year	1 in 1000 $\geq p \geq$ 1 in 100
Remote	2	Unlikely to occur in an operational year	1000000 $\geq p \geq$ 1 in 1000
Improbable	1	So unlikely, it can be assumed occurrence may not be experienced	$p \leq$ 1 in 1.000.000

Table 6.4: Safety Risk Impact Severity

Keyword	Level	Description
Negligible	1	Slightly affecting RCR quality and efficiency; no impact on airside operations or runway opening.
Minor	2	Causes a minor delay ($\leq$ 10 min) in runway opening due to safety controls; minimal disruption to flight schedules.
Moderate	3	Causes a significant delay (10 min - 60 min) in runway opening, requires additional clearance procedures; may incur minor damage to drone or non-critical ground equipment.
Major	4	Forces runway out of service; all aircraft movements halted or rerouted until mitigation actions are complete, requiring extensive recovery procedures.
Catastrophic	5	Complete suspension of airside operations (zero-rate operations); high likelihood of collision with aircraft or damage to critical infrastructure.

6.5.3 Risk Evaluation

A risk can essentially be described as probability times severity (Roelen et al., 2021). Using the mentioned metrics, each parameter deviation has been evaluated with the resulting risk score. The parameters risk scores are combined into an overview, see Table 6.5 and plotted see Figure 6.1. Identified risks are placed in three score categories: low risk (1-6)—Risk Zone 1, represented by green, medium risk (8-12)—Risk Zone 2, represented as yellow and high Risks (15-20) —Zone 3 Represented as red.

Risk Table

The findings are presented in Table 6.5, the basis for further discussions and based on an example by Hikmet Karakoc et al. (2021). For the full analysis of these risks, see worksheets in Appendix J.

Table 6.5: Risk Scoring Overview

No	Parameter	Guideword	Probability	Severity	Score
4-5:1	Free airspace	Not	4	4	16
8-1:1	Emergency Landing Trigger	None	3	5	15
6-3:2	Control Integrity	Other than	3	5	15
4-1:3	Altitude	None	3	4	12
6-2:2	Control Integrity	Less	3	4	12
6-2:1	Control Integrity	None	2	5	10
6-1:2	Signal Strength	Less	3	3	9
7-1:1	RTH Trigger	None	3	3	9
2-1:2	Mission Trigger	Other than	2	4	8
5-1:1	Sensor Calibration	Other than	4	2	8
8-2:2	Descent speed	more	2	4	8
1-2:2	Sensor Ready	Other than	3	2	6
4-1:2	Altitude	Less	2	3	6
4-3:2	Horizontal Positioning	Other than	3	2	6
4-3:3	Horizontal Positioning	Other than	2	3	6
6-1:1	Signal Strength	None	2	3	6
7-2:1	Navigation Path	None	2	3	6
7-2:2	Navigation Path	Other than	2	3	6
7-3:1	RTH Altitude	Less	2	3	6
7-3:2	RTH Altitude	More	2	3	6
8-1:2	Emergency Landing Trigger	Other than	2	3	6
8-2:1	Descent speed	less	2	3	6
8-3:1	Shutdown Sequence	Not	2	3	6
9-1:1	Docking Alignment	No	3	2	6
9-3:1	Data Offloading	No	3	2	6
5-3:1	Data Quality	Less	5	1	5
1-1:1	Battery Charge	Less	4	1	4
1-2:1	Sensor Ready	No	4	1	4
3-1:1	Altitude	More	2	2	4
3-1:2	Altitude	Less	2	2	4
3-2:2	Arrival Location	Other than	2	2	4
4-1:1	Altitude	More	2	2	4
4-2:1	Velocity	More	2	2	4
4-3:1	Horizontal Positioning	Other than	4	1	4
4-4:1	Battery charge	Less	2	2	4
5-2:1	Measurement Rate	Less	4	1	4
5-3:2	Data Quality	Other than	2	2	4
5-4:1	Geotagging Accuracy	Other than	2	2	4
7-1:2	RTH Trigger	Other than	2	2	4
9-4:2	Shutdown Sequence	Other than	2	2	4
1-3:1	GPS Lock	No	3	1	3
1-3:2	GPS Lock	Less	3	1	3
5-4:1	Geotagging Accuracy	Late	3	1	3
9-1:2	Docking Alignment	Other than	3	1	3
9-2:1	Power Transfer	None	3	1	3
9-2:2	Power Transfer	Less	3	1	3
9-3:2	Data Offloading	Less	3	1	3
3-2:1	Arrival Location	Other than	2	1	2
4-2:2	Velocity	Less	2	1	2
9-4:1	Shutdown Sequence	Not	2	1	2
2-1:1	Mission Trigger	None	1	1	1

Risk Matrix

The resulting risk scores are visualised in a matrix with probability as the x-axis and severity as the y-axis, in Figure 6.1, a common practice for risk assessments and one also common in the aviation sector as shown by Roelen et al. (2021) (Basavaraju et al., 2019). Similar to the work by Roelen et al. (2021), the three risk zones are represented in Figure 6.1 by their respective colours.

Although this evaluation benefits from the use of this approach, it is important to highlight the *risks* of using a risk matrix. Thomas, Bratvold, and Bickel (2014) concludes that risk matrices and risk scores, in general, suffer from several well-known weaknesses: for one, their determined category ranges force a smooth risk spectrum into only a handful of cells, often grouping different kinds of hazards, which might skewer the reader's intuition if not fully delving into the HAZOP worksheets. Additionally, multiplying probability and severity scores to get a single risk value has no firm mathematical basis, and can mislead rankings, resulting in poor allocation of resources. Yet the use of risk scores and matrixes for this study is deemed desirable. They have a clear informative value for subsequent conclusions, in the early stages of developing an autonomous drone trajectory, without having to bear to conscience of impactful misjudgements.

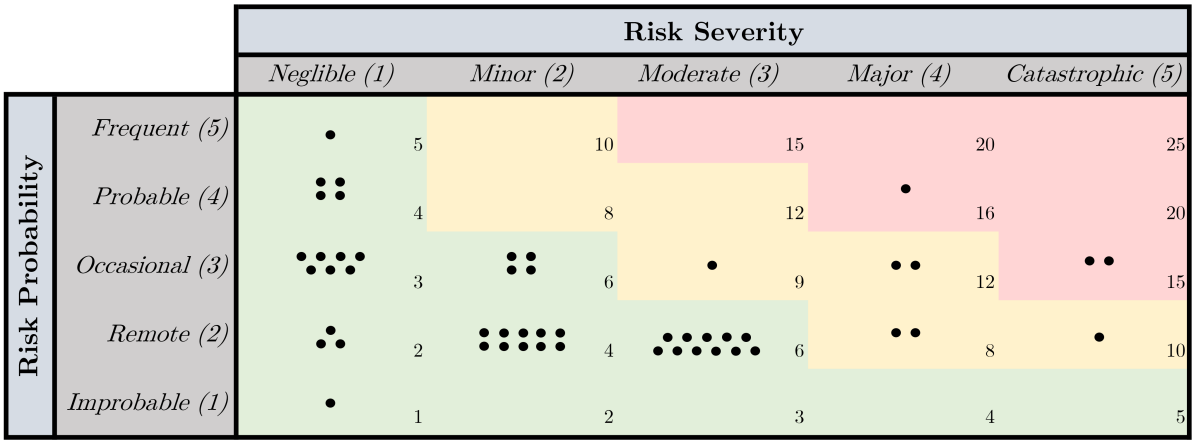


Figure 6.1: Risk Matrix

6.5.4 Discussion

The HAZOP safety meeting identified and evaluated autonomous drone RCR trajectory deviations across varying hazardous scenarios. Findings show that *Zone 3 risks occur in 3 out of 51 parameter deviations*. It is important to note, that various identified risks, often have the same root causes, but due to the deviation happening at different phases of the trajectory, the severity of the risk impact can vary. For example, if a drone has a ground collision due to internal system failure *above* the runway, this can lead to a runway shutdown, but when happening near a drone hub, it will not. The following risks stood out in the findings: *(see next page)*

Standout Risks

Among the system deviations identified in the HAZOP, a subset carries the greatest potential to disrupt airside continuity and compromise safety. These standout risks demand priority attention and robust controls before further system development or live deployment:

- **Compromised Airspace (4-5:1) (Score 16):** The airside is a dynamically moving environment, meaning that even if the drone trajectory is according to plan, external factors can interfere with operations. A compromised airspace, due to bird strikes or bird attacks is identified as highly probable (Probability 4) and would overwhelm the drone's internal systems causing serious operational disruption and runway shutdowns (Severity 4).
- **Loss of Control (6-3:2) (Score 15):** Loss of drone control due to jamming or spoofing of the control link is identified as likely (Probability 3) and highly disruptive. A compromised command channel can send the drone into restricted zones or result in total flight loss, causing severe operational disruption, whilst jamming and spoofing are also discussed to increase the chance of RTH and EL failure, resulting in a higher severity impact. Loss of control has a high chance of resulting in a temporary complete airside shutdown. (Severity 5).
- **Emergency Procedure Failure (8-1:1) (Score 15):** When both primary RTH and the secondary EL procedures fail, there is an uncontrolled drone on airside even without spoofing or jamming, requiring an immediate airside shutdown (Severity 5). This risk was thoroughly discussed during the safety meeting, and deemed possible to occur in an operational year (Probability 3), concluding that emergency procedures are crucial for operational integration.
- **Ground Collision (4-1:3) (Score 12):** As the drone trajectory operates at two meters height, a drone altitude deviation (Probability 3), whether due to an internal system or hardware malfunctions or due to wind gusts, would carry major operational consequences. The runway inspection is halted while the drone is being retrieved (Severity 3) but also until possible debris is cleared and surface integrity is verified, meaning a complete runway shutdown (Severity 4).

Common Root Causes

Throughout the HAZOP worksheets, these root cause categories recur the most frequently as drivers of trajectory deviations:

- **External Control Interference:** Throughout the HAZOP jamming and spoofing recur as a cause for high severity deviations. As they have the potential to be targeted interferences their probability is rated accordingly (Probability 3), motivated by the experience of safety advisors during the safety meeting.
- **Weather Disturbance:** Wind effects, such as sudden gusts or up/down drafts can introduce drift and trigger safety procedures. In some cases, due to the low altitude flight of RCR weather disturbances can result in ground collisions and a runway shutdown.
- **Payload Malfunction:** The MARWIS sensor either not installed properly, calibrated with incorrect offsets, or malfunctioning due to overuse is a recurring cause for failed drone trajectories, requiring subsequent inspection by Kievit (Severity 3). The sensor can also malfunction due to drone flight accuracy, and together this root cause accumulates to a high probability.
- **Drone Internal System or Hardware Failure:** Various drone system failures return in the worksheets as causes for system deviations, prompting a reliable drone system. Malfunctions in critical subsystems, such as GPS calibration or mission trigger logic, are direct causes for failed trajectories and if happening at an unfortunate phase, could lead to unsafe flight behaviour and unplanned deviations. Hardware malfunctions due to overuse also can lead to unwanted behaviour.
- **Hub Interaction Malfunction:** A returning cause for failed trajectories causing low severity risks is interaction failure between the drone system and the hub infrastructure—such as missing external energy at the drone hub or ageing battery cells— that undermines launch capability and flight specifications.

Common Consequences and Their Operational Impact

Across all HAZOP deviations, a couple recurring consequence patterns are identified, requiring subsequent operational mitigation for their impact:

- **Pre-mission Failure Preventing Trajectory Execution:** Deviations during the pre-mission phase prevent the drone from initiating its trajectory. In these cases, the Kievit completes the runway inspection, avoiding any delay in runway reopening (Severity 1) but reducing overall inspection efficiency introduced by using the autonomous drone trajectory.
- **Incomplete or Corrupted Data Reports:** Data quality or hub connection errors can produce partial inspection outputs, requiring post-mission evaluation and interpretation, but not requiring full re-inspection (Severity 1).
- **In-flight Deviation Triggers RTH:** Once airborne, any significant deviation forces the drone to abort mission and return to a hub. The Kievit can only take over runway inspection tasks once the drone has successfully returned, therefore causing a larger delay in runway opening (Severity 2).
- **Stranded Drone Requires Ground Retrieval:** Occasionally the drone neither finishes their trajectory nor reaches the hub, necessitating manual recovery by Kievit , before being able to conduct the runway inspection, and thus leading to a larger operational delay (Severity 3).
- **Escalating Fallback Procedures:** If the drone exits its designated corridor, it first attempts a RTH, which would be followed by a Kievit replacement inspection (Severity 3) after completing its RTH; failure of the RTH trigger is followed by triggering of an EL (Severity 4), requiring a Kievit to retrieve this drone, before finishing of the runway inspection. It is also a possibility, that EL fails to trigger which leads to a catastrophic level event (Severity 5), where a zero-rate is given and the airside shuts down until mitigating this uncontrolled drone.

Proposed Preventative Measures

During the safety meeting, the team identified a range of safeguards for various parameter deviations. After post-processing, these were grouped into the following preventative measures:

- **Assure System Component Reliability:** A crucial aspect of an autonomous drone for this specific trajectory is assuring consistent functionality of all three system components: the drone, the payload and the hubs. This is achieved by uninterrupted and redundant power systems, regular system health checks, scheduled maintenance and excessive pre-implementation testing, for all identified parameter deviations.
- **Develop Trajectory Integrity Protection:** Geofences require the development of low- and high-altitude precision tailored to flight testing conclusions, including speed governors and GPS assurance with RTK repeaters along the trajectory to safeguard the drone on its planned path.
- **Develop Emergency Procedures & Retrieval Protocols:** A key aspect of autonomous drone integration assuring that emergency procedures work. To achieve this, emergency procedure developments need to be explored and tested, including the use of trigger confirmation delay with dual conditions—system trigger plus external acknowledgement— and developing protocols for streamlined retrieval procedures to minimise runway downtime.
- **Assure Communication & Control Resilience:** As jamming and spoofing are identified as common causes for high severity system deviations, preventing is crucial. By developing continuous monitoring capabilities throughout the trajectory communication and control deviation probabilities could be kept to a minimum due to timely manual interventions. Additionally development of internal system protection and redundant manual override possibilities by in-house safety systems is crucial to prevent risks caused by unauthorized parties.
- **Extend Wildlife Management:** By extending Schiphol's airside wildlife management to include drone-bird interaction and develop targeted solution approaches to bird types known to interfere with drone systems, compromised airspace risks could be prevented, aiding in minimising collisions.

6.6 Review Meetings

Following the safety meeting, four review sessions were held to revisit the HAZOP findings and assess the risk evaluations, according to best practices by Rausand (2011). Due to practical difficulties, the HAZOP team could not meet together; instead, each review meeting was held with an individual partitioner or expert to ensure completeness and cross-validation of the results. Table 6.6 lists the objective and participants for each session. Outcomes of these review meetings are iteratively incorporated into the HAZOP worksheets, leading to the complete assessment and subsequent findings.

Table 6.6: Review Meetings

Objective	Company	Role	#
"Reviewing drone deviation probabilities."	Helix Aviation	M350RTK Expert	R1
"Reviewing sensor deviation probabilities."	OTT Hydromet	MARWIS Expert	R2
"Reviewing consequence severities and regulation."	LVNL	Drone Risk Expert	R3
"Reviewing overall HAZOP study."	Royal Schiphol Group	Safety Advisor	R4

All four sessions were conducted consecutively on 26 May 2025 to ensure proper follow-up and coherent integration of expert feedback into the worksheets and final outcomes. Summaries of the review meetings can be found in Appendix I.2

6.7 Study Limitations

The following limitations were identified with regards to the Risk assessment, some of which overlap with typical HAZOP limitations pre-identified in Section 6.3.2.

- A fundamental limitation originated from the innovative aspect surrounding autonomous drone operations at Schiphol Airport: without existing procedures or regulatory frameworks, it was difficult to establish clear protocols for action assignments and stakeholder responsibility. As there are also no comparable autonomous-drone trajectories at other airports, appropriate benchmarking of known failure modes for the specific environment or adaptation of established best practices for risk identification and mitigation were not possible.
- During the primary safety meeting, there was no participant with in-depth expertise in drone system failure or sensor failure probabilities, necessitating review meetings; this absence of initial insight into failure probabilities may have affected early risk scoring. Additionally, during the review meeting, sensor deviation probabilities were assessed by an expert directly involved with the production of the sensor thus introducing bias in the determination.
- The HAZOP method relies heavily on the subjective judgments of its team, introducing potential bias, particularly in severity and probability ratings. It would be interesting to know how the selection of team members affected the results, and further the research with a secondary validation safety meeting with the same approach but with different team members.
- Constrained by the role as intern limited to a single HAZOP session, the analysis could not benefit from multiple, shorter HAZOP meetings that might have allowed deeper exploration of complex deviations or more thorough cross-validation of findings. As a first-time HAZOP team leader lessons were learned throughout, which could be used for improved subsequent approaches.
- The study's scope was confined to the Polderbaan runway trajectory and its process nodes, intentionally excluding human-machine interface factors and broader organisational influences; as a result, certain procedural or managerial hazards may remain unaddressed.
- The inherently static nature of a HAZOP study cannot capture emergent hazards arising during live flights; without actual system trials, unforeseen interactions or failure modes may still surface if an autonomous drone enters operational service. Additionally, dynamic environmental factors such as sudden weather shifts or various wildlife patterns, were only qualitatively incorporated, limiting the precision of quantitative risk estimates.

6.8 Chapter Summary

Chapter 8 aimed to answer the question ***"What operational risks and safety impacts arise by using autonomous drones for runway condition reporting, and how can these risks be mitigated?***.

To answer this question the developed Polderbaan optimised drone trajectory was assessed for risks through a tailored HAZOP study. The risk assessment had three primary purposes: first, to identify deviations from intended operations and their root causes; second, to evaluate risks in terms of probability and severity; and third, to propose safeguards and actions that could progress safe autonomous drone integration into Schiphol's airside. By forming a multidisciplinary safety meeting team with help from Schiphols Safety Department, which included Schiphol safety advisors, FMA, APM, and LVNL drone risk experts, the HAZOP safety meeting dissected the three developed trajectory phases—pre-mission, mission and post-mission—into parameters deviations guided by established HAZOP guidewords. Key outcomes include a prioritized list of high-risk deviations and their risk scores, recurring root causes and their consequences. Standout risks are *compromised airspace, loss of drone Control, failure of emergency procedures and ground collisions.* During the safety meeting, but also in post-processing, preventive measures were developed, including *system reliability assurance, trajectory integrity protection, emergency procedure redundancy and retrieval protocols, communication and control resilience and advanced wildlife management*. These preventative measures are found to be able to mitigate the majority of identified risks, and their impact on probabilities and severities should be subject to future research.

Although this HAZOP was constrained by various limitations including the novelty of autonomous drones at Schiphol, resulting in limited action assignments and relying on expert intuition for probability estimates, it establishes a baseline risk profile for autonomous drone use and answered the sub-question by identifying operational risks and safety impacts. Ultimately, the chapter demonstrates that early, systematic risk assessment uncovers relevant system deviations, informs procedural safeguards, and guides iterative improvements before innovation development.

7 Visualisation Model

This chapter funnels the findings of preceding chapters—a feasible drone system, an optimised flight trajectory and protocol and associated airside risks—into a combined visualisation model. This data-driven model visualises RCR by autonomous drone and allows for subsequent case study insights.

7.1 Goal & Motivation

The goal of the data-driven model is to visualize the developed case study, to achieve three objectives: *stakeholder comprehension of the developed innovation* and *case study data insights* with which general expectations can be set for autonomous RCR.

Using ABM it is possible to model the M350RTK drone as an agent with flight trajectories and protocol determined in Chapter 5. By using historical Schiphol operational data, these trajectories can be visualized in an operationally representative environment. The goal of this chapter is *not* to make a simulation model able to analyse emergent drone behaviour across many various scenarios, although this is included in future research recommendations, see Chapter 10.

7.2 Approach

1. **Conceptualisation:** Defines the model structure and agent-based logic used to simulate autonomous RCR operations.
2. **Specification:** Outlines key model assumptions, input parameters, and behavioural rules for agents and model components.
3. **Data Integration:** Describes the datasets used to represent operational conditions at Schiphol Airside, including aircraft movements and inspection schedules.
4. **Visual Data Analysis Outcomes:** Presents model-generated insights through visual outputs, highlighting inspection frequencies, route overlaps, and potential operational conflicts.

7.3 Conceptualisation

7.3.1 Agents

The model consists of three agent types: *Drone*, *Kievit* and *Aircraft*. In this visualisation model, there are three Kievits active, and hundreds of operational aircraft, arriving and departing on the modelled day. Both of these agent types are data-driven, their behaviour is completely based on historical GPS data obtained from Royal Schiphol Group, meaning that their behaviour is not reactive to drone behaviour. A drone agent is modelled for each runway, according to flight trajectory and protocol described in Chapter 5. It has been opted to model all runway trajectories and not just the Polderbaan, for which the risk assessment has been done, resulting in less conclusive performance drone insights but a more comprehensive total picture.

7.3.2 Conceptual Model

The conceptual model comprises four key components: *independent variables, control variables, structural parameters and dependent variables*. During each run, the model ingests the independent inputs for specific data, applies its control logic to dispatch agents along the specified routes when triggered, and uses the structural parameters to bind their behaviour. See Figure 7.1.

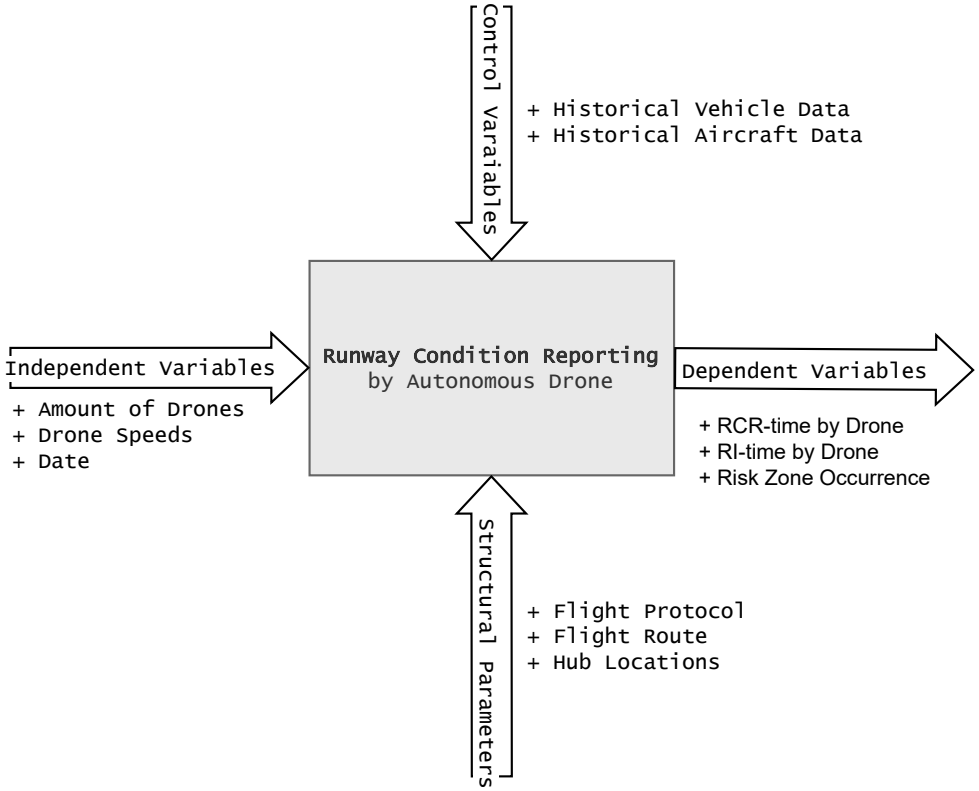


Figure 7.1: Conceptual model.

7.3.3 Drone Agent Logic

As the only non data-driven agent type described in the model are drones, and there is no interaction between these agents, each of the six drone agent-types follow a described flow, see Figure 7.2.

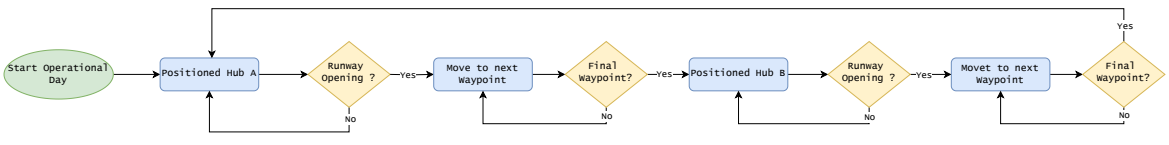


Figure 7.2: Drone Logic Flowchart

7.4 Model Specification

7.4.1 Assumptions

Table 7.1: Model Assumptions

Type	Assumption
Drone	1. Drone flight speed is consistent as determined in the trajectory design. 2. Drone trajectories are not affected by weather conditions. 3. Drones always execute and complete their trajectory according to design. 4. Drone ascent and descent are not taking in to account during taxi times. 5. Drone are not able to execute emergency procedures.
Kievit	6. Only actively transponding Kievits are analysed. 7. All full runway traverses are deemed to be runway inspections.
Aircraft	8. Only actively transponding aircraft are analysed. 9. Aircraft are only analysed for GPS location, not for size or other factors
Runway	10. Runways have only three states, closed, checking and open. 11. Runways open directly after RCR is completed. 12. Runway states change to 'closed' if they host other traffic than arrival and departure, otherwise they are 'idled' as open runways.

7.4.2 Variable Specifications

Table 7.2: Specification of Model Variables

Agent-type	Variable	Value	Source
Drones	Taxi speed	20 m/s	Table 5.1
	Mission Speed	20 m/s	Table 5.1
	Ascent Speed	6 m/s	Table 5.1
	Descent Speed	5 m/s	Table 5.1

7.5 Data Integration:

To visualize the autonomous drone trajectories in the operational environment of Schiphol Airside, this data-driven visualisation model integrates two internal Schiphol data sets. For the scope of the model, it was decided to analyse one operational day—15-12-2024—a randomly chosen day in December 2024. December was deemed interesting, as weather conditions are expected to increase the number of times a runway inspection is required, as determined in Chapter 4. The following two data sets were used:

- *Historical Kievit Transponder Data [15-12-2024]:* Data set containing GPS transponded positions per second, for three Kievits that were active on that operational day, the 15th of November 2024.
- *Historical Aircraft Movement Transponder Data [15-12-2024]:* Data set containing GPS transponded positions per second of aircraft, that were arriving or departing Schiphol Airport on that operational day, the 15th of November 2024.

A key aspect of the model is that the drone trajectory is executed when the runway inspection protocol is started by LVNL. The dataset "LVNL-Usage" containing the precise moments that runway opening started, was not available during the internship, requiring the need to derive the precise runway opening moments by visualizing the two available data sets. By visualising Kievits inspecting the runway, and the aircraft utilizing the runway after that inspection, it was able to derive when the runways opened, and when the drone could execute its trajectory according to the designed protocol.

7.6 Airside Visualisation

Figure 7.3 shows the main visualisation of the model, utilizing various open source maps (Jawg Maps & OpenStreetMap contributors, 2025; OpenStreetMap contributors, 2025). Aircraft are depicted as blue, Kievits are depicted as pink and Drones are depicted as red circles on black drone hubs. There are six runways, either *open (green)*, being *inspected (orange)* or *closed (red)*.

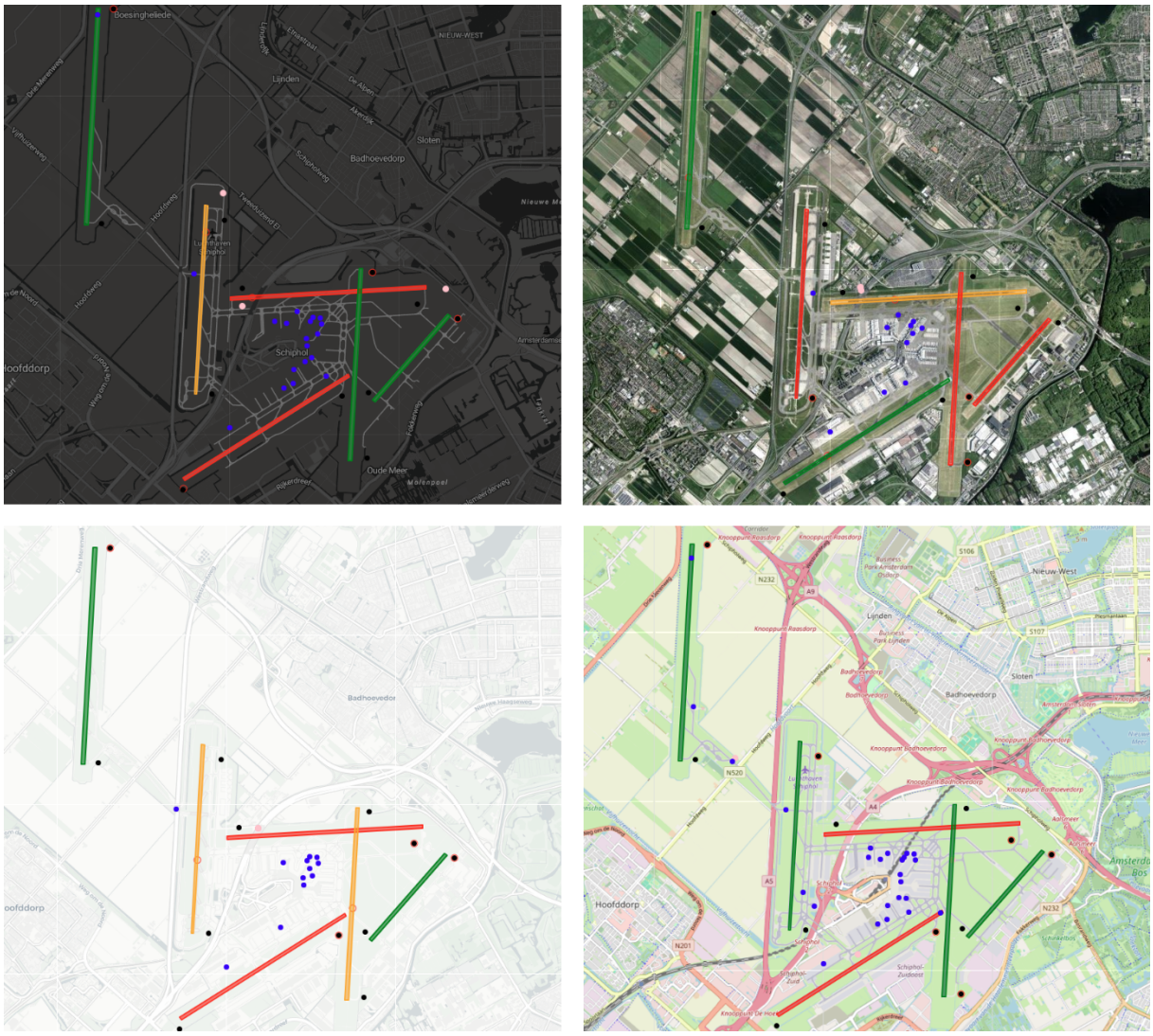


Figure 7.3: Airside Visualisation

7.7 Model Analysis Outcomes

The visualisation model makes it possible to analyse the drone trajectories, aircraft movements and Kievit inspections, along one full operational day. Visualizing the airside plays a role in gaining an understanding of the environment and makes it possible to approach questions such as *"How often is each drone required to report a runway condition?"* and *"What is the average duration of a drone to inspect a runway?"*, without quantifying variability or confidence intervals. Since the model covers only a single operational day, these metrics serve as a baseline "snapshot" of system performance; future work could extend this model to cover a range of settings and produce more elaborate metric values for further analysis. Data analysis outcomes are presented in Table 7.3

Table 7.3: Data Analysis Outcomes

Metric	Value	Origin		Notes
Flight Arrivals	630	Polderbaan	439	Polderbaan is continuous use throughout the day, Zwanenburgbaan is used during high arrival traffic, and is traversed by taxiing aircraft from the Polderbaan when not in use.
		Zwanenburg	181	
		Oostbaan	10	
Flight Departures	641	Aalsmeer	368	Aircraft depart the Aalsmeerbaan and Kaagbaan from various runway locations, often with two aircraft lined up on the runway at the same time.
		Kaagbaan	262	
		Oostbaan	11	
Runway Inspections	27	Polderbaan	6	Oostbaan has a high amount of runway inspections for the arrival and departures it facilitates.
		Kaagbaan	6	
		Oostbaan	6	
		Zwanenburg	5	
		Aalsmeer	4	
Total Drone Flight Time	1h45m	Polderbaan	33:43	At full operational use, there would be 1h45m of Drone flight time across the six drones at Schiphol Airport
		Kaagbaan	24:06	
		Zwanenburg	20:25	
		Aalsmeer	16:48	
		Oostbaan	15:06	
Average Drone RCR-time	2:58	Polderbaan	3:41	For the Polderbaan the optimal hub placement was found, for the other hubs this was a rough estimate, therefore impacting their outcomes.
		Aalsmeer	3:09	
		Zwanenburg	3:04	
		Kaagbaan	3:01	
		Oostbaan	1:53	
Average Kievit RI-time	$\sim$ 4:10	Aalsmeer	4:23	As Initial Runway inspections and intermediate runway inspections differ in intensity, the metric values should be perceived as a informative value for duration of Kievit activity on runway.
		Zwanenburg	4:12	
		Polderbaan	4:05	
		Kaagbaan	4:05	
		Oostbaan	4:05	
Risk Zone 3 Occurrence	81	Polderbaan	18	At full operational use, the six drones cause the occurrence of 81 identified Risk Zone 3 situations, as described in Chapter 6.1
		Kaagbaan	18	
		Oostbaan	18	
		Zwanenburg	15	
		Aalsmeerbaan	12	
Risk Zone 2 Occurrence	216	Polderbaan	48	At full operational use, the six drones cause the occurrence of 216 identified Risk Zone 2 situations, as described in Chapter 6.1
		Kaagbaan	48	
		Oostbaan	48	
		Zwanenburg	40	
		Aalsmeerbaan	32	
Risk Zone 1 Occurrence	1080	Polderbaan	240	At full operational use, the six drones cause the occurrence of 1080 identified Risk Zone 1 situations, as described in Chapter 6.1
		Kaagbaan	240	
		Oostbaan	240	
		Zwanenburg	200	
		Aalsmeerbaan	160	

7.7.1 Runway Usage and Inspection Periods Insights

Figure 7.4 presents the runway usage and inspection periods for 15 December 2024. While the actual drone inspection takes approximately 4 minutes, see Tabel 7.3 the inspection segments depicted as red in Figure 7.4 include the idle buffer time preceding runway opening. Notably, the initial inspections for both the Polderbaan and Kaagbaan occurred prior to the start of the observed operational window. In contrast, the Kaagbaan and Oostbaan underwent additional inspections at the end of the day, while the Polderbaan, Aalsmeerbaan, and Zwanenburgbaan did not.

This figure offers insight into when autonomous drone operations could be scheduled and highlights periods where multiple inspections would have occurred simultaneously under the proposed flight protocol. Figure 7.4 shows that at 11:30 and 12:45 three autonomous drone inspections occurred at the same time. Such overlaps would introduce coordination challenges or bottlenecks for drone operations under the current CTR regulations—limiting Schiphol airspace to a maximum of two drones.

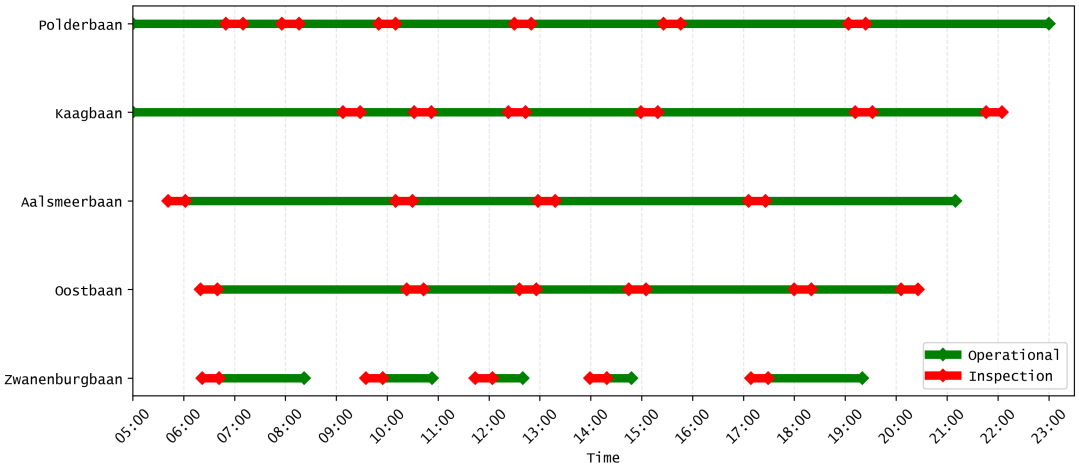


Figure 7.4: Runway Inspection and Operational Schedule.

7.7.2 Accumulated Drone and Kievit Paths

Figure 7.5 shows the accumulated RCR and runway inspection routes over the operational day. On the left, all executed drone routes are visualized, according to the trajectory design development. On the right, the Kievit transponder data can be seen, showing Kievits driving over the runway for inspections.



Figure 7.5: Accumulated RCR and RI Routes.

7.7.3 Notable Observations

- *General:* Runway inspections are consistently scheduled approximately 15 minutes before a runway opens for arrivals or departures.
- *Polderbaan:* The Polderbaan is continuously in use, hosting the largest amount of traffic. Notably, Schiphol hosted arrivals for two hours after the last departure, all arriving at the Polderbaan.
- *Zwanenburgbaan:* Where other runways are 'idled' when not being used for arrivals or departures, and requiring re-inspection before they can be used once more, the Zwanenburgbaan actually closes down. This is because it hosts taxiing aircraft from the Polderbaan, as a shortcut. Approximately five minutes following one of the runway inspections at the Zwanenburgbaan, aircraft taxiing from Polderbaan continued to cross Zwanenburgbaan, showing that aircraft may not impact the runway condition. Immediately after the last landing, crossing traffic resumed once again. These observations show operational efficiency but also procedural tightness.
- *Buitenveldertbaan:* Although the Buitenveldertbaan was not utilized for operations on this day, there were multiple Kievit runway traverses, approximately every few hours.
- *Aalsmeerbaan:* Consistently all inspections started from the south end of the runway, this is only seen at the Aalsmeerbaan. The Aalsmeerbaan during this operational day was in heavy use, with sometimes six aircraft queued up for departure.
- *Kaagbaan:* During peak hours aircraft lined up at two or even three locations on the runway, showing the operational efficiency.
- *Oostbaan:* This runway is used infrequently; when it was active alongside Aalsmeerbaan, Aalsmeerbaan traffic had to wait for an Oostbaan departure. Oostbaan was the only runway that switched between arrivals and departures on the observed day, and no inspection took place between that switch, diverging from Schiphol protocols (Royal Schiphol Group, 2024c). Departing flights make a sharp left turn after take-off to the south, avoiding overlap with Aalsmeerbaan airspace. A late-evening inspection was not followed by a departure or arrival, meaning there might have been another inspection reason undefined by the data set.

7.8 Chapter Summary

Chapter 7 aimed to answer the question ***"How can a visualisation model demonstrate the integration of autonomous drones into Schiphol Airport's airside for runway condition reporting, and what insights can be drawn from data-driven visual analysis?"***.

To answer this question, a visualisation model was developed using ABM bringing together early chapter findings into a single, data-driven environment. Through the integration of historical aircraft and Kievit transponder data, the model situates the drone agents in a simplified operational context. The model was used in explaining the developed drone integration to stakeholders during the safety meeting—by allowing the behaviour of autonomous RCR operations to be observed alongside real-world airside activity. The data-driven model enabled a series of visual data insights revealing operational patterns and airside occurrences, such as RCR durations per runway, drone usage frequency, and a tally of airside risk zone occurrences per trajectory. These results helped ground the case study in data and offered a foundation for initial analysis of the drone's fit within current airport workflows. Furthermore, the model was presented in coordination meetings with key stakeholders DDO, FMA, APM and LVNL, see Section 4.3. In the safety meeting, the visualisation served as an initial guidance in explaining the topic of discussion.

8 Discussion

This thesis addressed four sub-questions, aligned with the dimensions of reliability, effectiveness, and safety described in Chapter 3. In this discussion, the results of each chapter are reflected upon in relation to the overarching case study. Following this, the scientific contribution of the findings is described, and the study's limitations are discussed, to provide a balanced interpretation of the findings.

8.1 Results

The result discussion revisits each sub-questions findings and their contribution to the overall case study. For more information on each sub-question see Chapter 3.

- **[S1]** Findings of Chapter 4, show that commercially available drone systems are, on paper, technically feasible to perform autonomous RCR at Schiphol Airport using a dual hub system. A criteria-based selection process, formulated by Schiphol-specific weather data, Schiphol-specific runway specifications, and Schiphol-specific sensor equipment, identified the following criteria parameters metrics: *wind resistance* $\geq$ *12 m/s*, *IP-rating* $\geq$ *IP43*, *sub-decimetre flight accuracy*, *battery endurance of* $\geq$ *15 minutes*, and *payload capacity of* $\geq$ *1.7 kg*. A comparative evaluation using WDM, supported by expert-validated criteria weighting, identified M350RTK as best fitting for these criteria. The system's compatibility with dual-hub docking infrastructure, dissected through a system integrity overview and validated through expert insights further reinforced its technical feasibility for RCR. A subsequent weather impact analysis showed that temperature, precipitation, and average wind speeds pose no disruption to M350RTK 24-hour operability, while wind gusts do—affecting approximately 64% of operational days, posing as an operational limiting factor. The expert interviews reinforced this finding, by consistently identifying wind performance as the most critical constraint. Sensitivity analysis findings showed that a 1.6% increase of wind tolerance increases operable days by 13%, in line with expectations set by Gao et al. (2021), who states that wind threshold increase realises the largest operation gain across weather conditions. Notably, two experts indicated that the real-world performance of M350RTK has shown to exceed the stated wind threshold, suggesting a potential margin for operational flexibility.

  These findings collectively validate that autonomous RCR using the M350RTK is technically feasible but constrained by weather conditions, with conclusions on reliability drawn in Section 9.1. The finding supports the case study progression by selecting M350RTK as the reference system for subsequent research. M350RTK technical specifications constrain the trajectory optimization research and the system poses a reference case for system deviations discussed in the HAZOP analysis.

- **[S2]** Findings of Chapter 5, portray an optimised flight trajectory under constrained conditions, complemented by a protocol design for autonomous RCR at the Polderbaan. Using OR methodology, a RCR trajectory was framed as an optimization problem, aiming to minimise flight time while satisfying runway, technical, and operational constraints. This optimisation resulted in a trajectory with a flight duration of *3 minutes and 41 seconds*. In this trajectory, flight protocol facilitates the drone departing and ascending from Hub A, taxiing to the runway start, traversing the runway and taxiing and descending to Hub B. Trajectory optimisation was predominantly optimised for its taxiing route, constrained by the hub placement—due to OLS and flight route — due to ILS. Findings also describe flight safety procedures accompanying the flight protocol: geofenced flight corridors segmented into three zones—green, orange and red—with according emergency procedures — a double redundant emergency procedure consisting of RTH and EL.

  These results establish an approach to RCR by autonomous drones at the Polderbaan, for which conclusions of effectiveness are drawn in Section 9.2. In the context of the overarching case study, this framework provides the necessary procedure for which subsequent HAZOP analyses the risks.

These findings allow for an evaluation of the probability and severity of system deviations associated with this autonomous approach to RCR.

- **[S3]** Findings of Chapter 6, assess the hazards surrounding an autonomous drone approach to RCR. Applying a tailored HAZOP analysis, assessing the optimised trajectory per flight phase, see Section5.3, resulted in a systematic identification of *51 drone parameter deviations*. The use of structured worksheets during the official Schiphol safety meeting, with described stakeholders including LVNL, DDO, APM, see section 4.3, enabled formulating risk profiles using probability and severity scales. From this, four key risks emerged as most critical due to their high probability–severity scores: *compromised airspace* —due to wildlife, *loss of drone control*— due to GPS spoofing or jamming, *emergency procedure failures*—due to internal system malfunctioning or signal jamming, and *ground collisions*—due to wind effects. These risks are deemed probable to occur sometime in an operational year, as described in Table 6.3. These risks directly relate to both external disruptions and internal system vulnerabilities and have the potential to seriously impact airside *safety* resulting in lengthy runway shutdowns or in some cases complete airport closure, see Table 6.4. Common root causes—*wind gusts, payload malfunctioning, and drone–hub interaction failures*—were repeatedly identified as probable.

  Findings show that one root cause can vary in severity, depending on *when* it happens during the flight trajectory. For example, When an internal system malfunction occurs above a runway and causes a ground collision, this results in a runway shutdown (Severity 4). But, when this same internal system malfunction happens elsewhere, for example near a drone hub, it does not result in a runway shutdown, but merely an operation delay (Severity 3).

  These results establish a wide risk overview of autonomous drone integration at airside for a specific task and divide the identified deviations into three risk zones with regard to severity and probability. The HAZOP safety meeting did not just identify hazards but also refined earlier trajectory optimization and protocol design, for example leading to a rerouted taxi path to avoid taxiways. Conclusions on the overall safety implications of an autonomous approach to RCR are drawn in Section 9.3. The risk assessment has been shown to reflect the key HAZOP concepts by Rausand (2011), who states that structured early–phase risk evaluation, even without live system trials, can shape system design and help determine the safety dimension of innovative development.

- **[S4]** Findings of Chapter 7 were derived by developing a data-driven visualisation model integrating findings of previous chapters. This visualisation model gave insights into autonomous drone integration into airside: by combining historical Kievit and aircraft transponder data with agent-based drone modelling, it was possible to analyse the developed drone case study in a modelled airside environment. The data analysis of the model resulted in snapshot insights into average drone inspection durations over all runways—approximately *2:58 minutes*, runway inspection frequencies — *27 times in one operational day*, and the distribution of HAZOP identified risk zone incursions— *of which 81 zone 3 risks* in an operational day. These findings provide an initial estimate of operational impact of drone RCR. Further, the model data analysis showed simultaneous drone RCR operations on multiple occasions, hinting at potential operational bottlenecks relevant for stakeholders LVNL and DDO under current CTR regulation.

  The data-driven visualisation model not only allowed for the analysis of the operational drone trajectory and protocol within an airside context but also served as a communicative visual tool to approach stakeholder and illustrate the implications of the proposed approach to autonomous drone RCR.

Together, the findings of the four sub-questions combine as a case study of an autonomous drone approach to RCR. The identified technical feasibility (S1) directly constrained the flight trajectory and protocol design (S2), which in turn structured the scope and system of the risk assessment (S3). These findings came together in a visualisation model (S4). This progression reflects the logic of the Stage-Gate approach described in Chapter 3, and enabled iterative development and stakeholder input at each stage throughout the research.

8.2 Scientific Contribution

The described findings offer several scientific contributions to the field of autonomous drone integration in airport environments. By combining the reliability, effectiveness, and safety dimensions in a stakeholder-involved process, it advances specific insights befitting of a case study:

- This case study contributes to the development of autonomous drone integration at major airports by addressing two key challenges at Schiphol Airport identified by Gomez-Beldarrain et al. (2024): the lack of stakeholder consensus and the need to tailor autonomous approaches to specific operational contexts. By applying HAZOP analysis in collaboration with Schiphol stakeholders, and developing a context-specific approach to an autonomous operation, this thesis contributes to the knowledge gaps identified by Gomez-Beldarrain et al. (2024) with a exploratory use case example.
- The risk assessment contributes to scientific research into drones in complex environments by tailoring the HAZOP methodology to an early-stage design of an autonomous system. While previous HAZOP analysis into drones exist, such as Muram and Javed (2021) applying HAZOP in the context of drone networks, this research extends the methodology to a specific airside RCR task. Although varying in research objective, this study has similarities to research by Muram and Javed (2021): both address some of the same system deviations—such as GPS failures caused by jamming or spoofing—but in distinct operational settings. This thesis' research findings contribute as complementary research, but also as comparative research. This allows for a possibility for future research to assess the applicability of HAZOP in diverse scenarios.
- The technical feasibility analysis in this study contributes a use case example of how weather conditions are expected to impact drone operations at a major airport. It contextualizes research findings by Gao et al. (2021), who identified wind as one of the most critical limiting factors for drone flight. Using Schiphol-specific weather data, this study similarly highlights wind as the primary operational constraint, thereby reinforcing Gao et al. (2021) conclusion through a context-specific analysis.
- The constrained optimisation approach to an autonomous drone trajectory in a regulated airport environment, contributes scientifically as an application of findings by Gugan and Haque (2023), who synthesized various approaches to autonomous drone path planning and acknowledges the lack of practical implementations. Gugan and Haque (2023) stresses that future autonomous drone flight planning should consider optimisation, and have a protocol for realistic and dynamic environments. This study applied Schiphol-specific criteria, and developed an actual flight route according to airspace constraints, thus contributing scientifically as an exploratory use case. With further regard to trajectory and protocol findings, the design of geofenced flight corridors with associated safety protocols contextualizes a geofencing strategy described by Torens et al. (2020). By providing an airside visualisation model including airside aircraft, this thesis complements flight planning approaches discussed by Kim and Atkins (2022) to a certain level, which concludes the need for flight path planning to incorporate aircraft dynamics.

Overall, this thesis contributes a case study that explores the dimensions and challenges of autonomous drone integration in an airport environment, in terms of reliability, safety, and effectiveness. While it does not claim to deliver generalizable conclusions about large-scale implementation, it provides a systems-level view of a use case application, that could contribute to future development of airside drone operations.

8.3 Limitations

As study findings aim to contribute scientifically, it is important to acknowledge the limitations that impact the generalizability and conclusiveness of these results. This thesis was designed as an exploratory case study, omitting practical and empirical testing, meaning each stage inherently involves assumptions and simplifications. The following section reflects on key limitations:

- **[S1]** The analytical nature of the conducted technical feasibility analysis results in limiting factor in assessing the reliability of the M350RTK drone system: while the evaluation is grounded in system specifications, stakeholder-informed criteria, and historical weather data, it does not involve real-world flight testing or physical proof of a developed dual-hub docking infrastructure. As such, subsequent conclusions on reliability rest on specifications rather than actual performance. Although four expert interviews were conducted to strengthen the practical relevance and credibility of the analysis, the absence of an engineering proof-of-concept limits the conclusiveness of the findings. For instance, while wind gusts are identified as the primary operational constraint, the actual impact of such wind gusts on system behaviour above a runway remains untested. Thus, while the M350RTK can meet defined criteria on paper, its real-world reliability for autonomous RCR at Schiphol remains to be validated through field testing.
- **[S2]** Although the identified constraints, for which the trajectory was designed, give a good idea of Schiphol airside, it also highlighted the limited depth the OR framing could explore in the time constraints of the study. Integrating autonomous drones in airside is a large endeavour, and stating an optimised flight path with a selection of constraints affects the conclusiveness of the findings. Additionally, even though the chapter is submerged in operational experiences and aviation guidelines, it is affected, similar to the technical feasibility analysis, by the omission of practical testing: to effectively set up a trajectory that can be proven to be effective, actual trials are required. This limitation can be seen as a double-edged sword: it forces the subsequent HAZOP to analyse a system that isn't fully developed—yielding less groundbreaking conclusions—yet it also aligns with the core goal of a HAZOP, which is to identify hazards at an early stage of the development of a system.
- **[S3]** Key limitations regarding the conducted risk assessment are described in Section 6.7. While HAZOP enables a structured identification of safety deviations and yielded co-developed outcomes, the absence of practical knowledge on drone use at airside during the safety meetings constrained the ability to validate the assessed risks. Probability and severity scores were based on stakeholder estimations rather than historical evidence, which introduces subjectivity and may skew prioritization—particularly in high-impact cases such as targeted GPS jamming. The novelty of autonomous drones on airside and the unavailability of drone system expertise during the safety meeting may have limited accuracy in those ratings. Further, the developed risk profile is inherently tied to a single, proposed trajectory at the Polderbaan, meaning changes to flight trajectory height, for example, would require reassessment. Finally, the study included one HAZOP session, which—while consistent with early-phase exploratory—was limited in iterative depth: alternative team compositions and phased sessions, would have likely yielded different results, which would be interesting for future research, see section 10
- **[S4]** The data-driven visualisation model, is subject to several limitations. First, it is restricted to modelling a single operational day, serving as the basis for the data analysis. This choice was made due to time constraints during model development. While it allowed for an initial exploration of drone integration, expanding the model to multiple days would have yielded more robust insights regarding Kievit activities and the operational fit of the six drones alongside aircraft. Additionally, the model is limited to visualising the optimised flight trajectory but does not include the emergency procedures—namely RTH and EL—that were designed as part of the operational protocol. This omission restricts the model's ability to reflect the full procedural design developed throughout this study. Finally, the visualisation model should also be further subject to validation to strengthen its results as a decision-support tool. While the model integrates validated historical data, it has not undergone formal validation procedures—such as calibration against operational benchmarks, expert-based verification, or scenario-based testing. This limits the extent to which the model's outputs can be confidently generalized. Future work should focus on validating the model's assumptions and data output to ensure conclusive integrity.

9 Conclusion

This thesis set out to explore a use case for autonomous drones at Schiphol Airport, in line with Schiphol's goal of an *autonomous airside*. The research concerned an autonomous drone approach to runway condition reporting, a runway inspection task that supports safe aircraft arrival and departure. Because RCR is a repetitive and time-consuming task with a linear workflow, it was identified as an interesting use case to explore how autonomous drones could be integrated into airside operations. This research approach resulted in the following main research question:

"How can drones be utilized reliably, effectively and safely within Schiphol Airport's operational environment to automate runway condition reporting?"

To answer this question, the research was framed around three dimensions: *reliability*, *effectiveness*, and *safety*. Each aspect was explored through a dedicated sub-question, which will be concluded in this chapter by assessing whether—-and to what extent—the proposed use case fulfilled the definition of each aspect as stated in Section 3.2. Following this, the implications of the case study findings are described specifically for Schiphol Airport, including a strategic outlook and policy recommendations.

9.1 Concluding Reliability

S1: "What technical specifications are required for a drone to reliably perform autonomous runway condition reporting under Schiphol Airport's environmental conditions?"

The study determined that to reliably perform autonomous RCR at Schiphol Airport, a drone system must meet a selection of Schiphol-specific criteria. These include a wind resistance of at least 12 m/s, an IP-rating of at least IP43, sub-decimetre flight accuracy, a minimum battery endurance of 15 minutes, and a payload capacity of at least 1.7 kg. Through a criteria-based evaluation supported by expert weighting, the M350RTK platform emerged as the most suitable candidate. Weather analysis indicated that temperature, precipitation, and average wind conditions generally allow for M350RTK flight, while wind gusts emerged as a limiting factor—with the max wind gusts per day restricting operations on roughly 36% of days over the past decade. Expert insights, obtained through semi-structured interviews supported this finding, with wind tolerance consistently identified as most critical for flight performance. Notably, small increases in wind resistance yield significant gains in operational days, underscoring wind threshold improvement as a key enabler for improved system reliability. Additionally, expert insights with practical M350RTK experience, hinted at a higher realistic wind threshold than current specifications suggest, reinforcing the need for in-field testing to better assess this reliability concern.

In conclusion, this study finds that, on paper, an autonomous drone system using M350RTK, MARWIS and two hubs, is technically feasible to perform RCR reliably at Schiphol Airport on approximately 64% of days under historical weather conditions. For the remaining days, however, the drone system would not be able to reliably execute RCR, due to wind gusts, shown to increase throughout the afternoon in an hourly weather analysis. This marks the current extent of the M350RTK's reliability dimension in the scope of this case study, underlining that *if* the proposed system were operational, continued reliance on Kievit RCR would be necessary on days when the drone system cannot operate reliably.

9.2 Concluding Effectiveness

S2: "What specific autonomous flight trajectory and operational protocols are required to effectively perform runway condition reporting at Schiphol Airport?"

In the study, the effectiveness of autonomous drones for RCR at Schiphol was addressed by designing an optimised flight trajectory and a supporting flight protocol tailored to airside constraints. The OR-based approach, yielded a trajectory optimisation that, on paper, minimises flight time to *3 minutes and 41 seconds*, predominantly constrained by the ILS critical areas impacting drone taxi routes. The designed flight protocol, supported by geofenced flight corridors, intended to trigger emergency procedures, including RTH and EL, serves as a supplement to the optimised trajectory. Together, the flight trajectory and protocol form a concept for autonomous RCR at the Polderbaan.

In conclusion, this study developed an autonomous drone approach to RCR, that on paper, can perform effectively within the constraints taken into account. The flight trajectory includes departure from drone hub A, a taxi route to the runway start, a traverse of the runway length, and taxiing and descent to hub B. While not tested in a live environment, the trajectory and protocol are considered as effective as possible given the analysed aspects in the scope of the study. Integrating the flight trajectory and protocol into a data-driven model, visualised these findings in a modelled airside environment, to help answer the fourth sub-question:

S4: "How can a visualisation model demonstrate the integration of autonomous drones into Schiphol Airport's airside for runway condition reporting, and what insights can be drawn from data-driven visual analysis?"

The model demonstrated *27 daily inspections* with a combined total of *1 hour and 45 minutes of drone flight time* across five runways on the operational day analysed. The visualisation model highlighted integration bottlenecks, due to simultaneous drone operations, not possible in current CTR. Insights gained within the scope of the model indicate the potential for drone-based efficiency improvements over current inspection methods. With an average inspection time of approximately *4 minutes and 10 seconds*, the drone approach hints at a RCR efficiency improvement of *roughly 1 minute per inspection* over current Kievit RCR. However, this finding remains highly dependent on the concluded extent of the effectiveness dimension and the limitations of the visualisation model, and should therefore be regarded as an indicative supplement to the dimension of effectiveness requiring further research.

9.3 Concluding Safety

S3: "What operational risks and safety impacts arise by using autonomous drones for runway condition reporting, and how can these risks be mitigated?"

The safety implications of using autonomous drones for runway condition reporting were assessed through a tailored HAZOP analysis of the developed flight trajectory. By segmenting the trajectory into three operational phases and systematically exploring potential parameter deviations, the analysis identified system vulnerabilities that can result in severe risks to the airport environment. Key risks are:

- **Compromised Airspace** due to wildlife.
- **Loss of Drone Control** due to GPS spoofing or signal jamming.
- **Emergency Procedure Failure** due internal system malfunctioning signal jamming.
- **Ground Collisions** due to wind gusts in combination with low trajectory altitude.

These risks are identified as having severe consequences—**runway closures or temporary airside shutdowns**— with a probability of occurring sometime in an operational year. In addition to these key risks, 48 further risks were identified along the trajectory, with potential airside impacts *ranging from minor additional tasking to significant operational delays.*

In conclusion, this study highlights risks associated with airside drones that translate into unacceptable safety impacts on airside. HAZOP findings show that autonomous drone RCR is not able to operate *safely*, without substantial risk mitigations. Key mitigation steps required before safe integration are ensuring *robust system integrity*, *validating emergency procedures consistency*, and *achieving high levels of resilience in communication and control system*. These proposed mitigations are identified as crucial, as they target the probability ratings of the majority of 51 identified consequences, including the key risks. The impact of these preventative measures on the risk probabilities is a topic for future research. Finally, these identified preventative measures may also be useful for the development of alternative use case applications of autonomous drones on airside.

9.4 Overall Case Study Conclusion

"How can drones be utilized reliably, effectively and safely within Schiphol Airport's operational environment to automate runway condition reporting?"

The findings of this thesis conclude that currently, an autonomous drone approach to runway condition reporting can, under constrained conditions, perform reliably when wind conditions allow, effectively within the analysed operational constraints, but **not** safely in the airside environment.

The HAZOP study shows that system deviations of the developed flight trajectory for autonomous drone RCR can lead to runway closures even airside shutdown. These deviations have the probability of occurring sometime in an operational year if using autonomous drones daily as proposed for RCR. Root causes for these system deviations must be mitigated before being able to satisfy the safety dimension of the main research question. If this dimension were to be satisfied, the case study indicates a potential for autonomous drones RCR at Schiphol Airport, when weather conditions allow, to contribute toward an autonomous airside, in line with the vision of Schiphol. This use case additionally has the potential to benefit operational efficiency, as cautiously indicated in this research. Further implications of the conclusions for Schiphol Airport, including a strategic outlook and policy recommendation follow in Section 9.5. Future research developments stemming from the conclusions are described in Section 10.

Taken together, on the one hand, the thesis findings point toward a potential for autonomous drones to operate in airside settings, but on the other hand, they highlight severe risks that render the autonomous drone approach unreasonable in the current environment. This case study provides a first-stage exploration of how autonomous drones could be utilized for runway condition reporting at Schiphol. The findings offer both a basis for future autonomous drone RCR development and a reference case for the broader progression of airside drone operations at Schiphol Airport.

9.5 Implications for Schiphol Airport

As this study was conducted in collaboration with Schiphol Airport, its findings are directly relevant to the airport's broader ambition of developing an *autonomous airside*. This section presents the implications of the research, described by a strategic outlook—assessing whether this case study merits further development within Schiphol's innovation strategy—and a set of policy recommendations on how developments could be pursued.

9.5.1 Strategic Outlook

Study findings show that drones offer the potential to automatise a key airside operation—but are accompanied by significant risk. Therefore, the strategic question is not whether autonomous drones can be utilized, but whether their utilization is desirable within Schiphol's current operational ambitions.

The safety meeting in collaboration with key Schiphol stakeholders concluded that in the current climate, integrating autonomous drones can not assure airside safety. This HAZOP approach revealed a dual perspective: on one hand, there is a strong belief amongst stakeholders that autonomous drones will play a role in future airside operations, but on the other hand, it is emphasised that operational use is currently not yet realistic. A strategic outlook is therefore to continue the discussion with key stakeholders, to find ways to pursue collaborative use cases, that *are* realistic in the current climate. Although this seems to place drones for tasks such as RCR strategically far in the future, safety advisors highlighted that even five years ago, the topic of drones would not have even reached the discussion table, suggesting a growing openness within Schiphol to explore drone use cases.

This case study targeted a repetitive task in one of the highest-risk zones of the airport: while this task is operationally well-suited for automation by drone, the high-risk implications make it less suitable as a starting point for real-world implementation. Strategically, this suggests that the time is not yet right to pursue full-scale deployment of autonomous drones over active runways. Instead, Schiphol's near-term focus should aim at smaller-scale use cases in lower-risk environments—tasks that are less safety-critical but still operationally meaningful. By taking this strategic approach, use case development can guide autonomous drone integration toward a context in which preventative measures are more thoroughly researched and implemented, paving the way for high-risk inspections by drones—such as RCR—to be deemed realistic.

This research concludes that autonomous drones **should** play an increasing role in the airport's innovation strategy—**but that RCR as a starting use case does not currently merit direct further research**. While the findings show that drones can occasionally be utilized reliably and effectively, the associated risks in this high-stakes environment make immediate implementation unrealistic. Instead, the focus should shift toward smaller-scale, lower-risk applications, the technology is ready and the organisational climate is receptive. According to insights gathered from stakeholder engagement throughout this research, **this is the right moment to begin that transition.** This thesis supports the described strategy by offering a case study with a clear risk assessment—built in collaboration with Schiphol stakeholders ——that, on paper, demonstrates the potential for efficiency gains for a fundamental autonomous airside operation. While full deployment remains out of reach for now, these findings can serve as strategic reference points in Schiphol's roadmap toward drone integration.

9.5.2 Policy Recommendations

1. **Clear communication with key stakeholders:** Stakeholders have strong opinions on drone integration at airports—and importantly, they want to be involved. This was especially evident during the HAZOP meeting, where their enthusiasm reflected an interest in shaping future developments. To support structured progress, it is recommended to introduce recurring development meetings specifically focused on drones, where visions and concerns can be discussed. In particular, it is advised to structurally involve LVNL for regulatory alignment, DDO for operational implementation, and APM for policy coordination. Other stakeholders—while still relevant—can be engaged more selectively, as drone development is currently less central to their responsibilities.

2. **Carefully weigh operational risks against expected benefits:** Future use case development should begin with a question: *do the potential benefits offered by an autonomous drone justify the potential risks?* Without a clear answer, full-scale deployment would be premature. This study identifies and quantifies key risks and potential effective improvements but is not positioned to provide a final verdict on the trade-off. Therefore it is recommended, before further development, to asses the risk-benefit trade-off, for which the HAZOP findings could be a starting point.

3. **Explore alternative low-risk use cases:** Schiphol's near-term drone strategy should focus on smaller-scale use cases in lower-risk environments. Based on the HAZOP findings, use cases are recommended where key risks—such as bird interference, and low-altitude wind effects—are less likely to occur. In particular, use cases that avoid operations near active runways or at low altitudes such as RCR are recommended:

    - *Foreign Object Debris Detection* in low-risk areas, such as cargo zones or remote aprons, could offer a match with the operational strengths of drones—particularly their flexible altitude range—and avoid the safety-critical pressures of high-traffic zones. These environments offer operational relevance without compromising safety.
    - *Asphalt Assessment:* During preliminary discussions with Heijmans B.V., a use case was suggested for drone-based asphalt assessment at the Buitenveldertbaan Maintenance scheduled for May 2025. This use case could explore efficiency improvements of a key stakeholder, and be trialled over an inactive, cleared runway.
    - *Marking Inspections:* APM stakeholders noted that marking inspections—currently performed manually from ground level—are labour-intensive. Drones could significantly improve efficiency by leveraging aerial perspectives. This task is well-suited for further investigation and can be trialled outside of the Schiphol airside, whilst still being applicable to Schiphol runways.

4. **Beware of regulatory progression required before future implementation:** Autonomous drone operations are currently restricted by airspace regulation, as the CTR allows only two drones, limiting limits large-scale deployment in the current airside environment. Coordination with LVNL, IenW, and EASA is essential to initiate the necessary regulatory pathways and possibilities. Actively developing drone use cases can play a key role in moving these regulations forward—and help build trust with regulatory stakeholders. It is important to further research where the regulatory difficulties lie, and how to develop use cases to impact regulatory standards. Discussions with the airspace authority LVNL have identified two possible regulatory strategies for enabling autonomous drone-based RCR at Schiphol. These options merit further exploration:

    - *Segregated Airspace for Runway Inspections:* Designating temporary, controlled airspace segments exclusively for drone use during inspection trajectory. Under this model, Schiphol would assume responsibility for these segments during inspections, bypassing LVNL oversight for the duration of operations. While this is complex for intersecting runways, LVNL has indicated that currently, this is the most realistic regulatory path.
    - *Advocating for a Drone Classification within Airspace Jurisdiction:* Schiphol could initiate or support efforts to redefine how drones are classified within controlled airspace. By distinguishing them from conventional aircraft, it becomes possible to develop dedicated protocols and enable more flexible access for operational use. This would involve engaging with national regulators IenW and contributing to discussions within the EASA framework to help shape future policy.

5. **Focus on M350RTK, but asses security risks:** It is recommended to approach future autonomous drone innovations with the M350RTK system. However, Schiphol operates within a high-security context, which means full reliance on third-party systems must be approached cautiously. A security assessment of the M350RTK system should be conducted, covering aspects such as data handling and remote access. This includes evaluating drone producer trustworthiness and potential geopolitical risks. To safeguard system integrity, Schiphol is recommended to pursue in-house development in collaboration with a trusted partner, retaining oversight and control over sensitive components.

10 Future Research

Due to the novelty of autonomous drones in airport settings, this thesis opted for an exploratory approach to reliability, effectiveness and safety. This approach concluded with a wide overview of the utilization of autonomous drones for a specific task, limiting to what extent each individual aspect could be analysed. Recognizing this, this chapter addresses how the three aspects require further research to aid the development of the innovation, followed by addressing possible model extensions for further insights on autonomous drone RCR. Three future researches stand as the most pressing:

1. *Researching Impact of Proposed Preventitive Measures, see Section 10.3*
2. *Further Protocol Design by Kievit Engagement, see Section10.2*
3. *Developing a Full Simulation Model for Autonomous Drone RCR, see Section 10.4*

10.1 Addressing Reliability

While this study presents a preliminary assessment of system reliability based on defined criteria and selected environmental data, further research is needed to fully understand—and eventually certify—the operational reliability of autonomous drones at Schiphol Airport. Additionally, it is also recommended that future research takes in to the account the developments of drone technology and their effects on reliability. In the scope of current advancements, the following directions are recommended:

- *Further Expand Weather Analysis:* This study evaluated drone operability based on hourly temperature, wind, wind gusts and precipitation data. Future research should examine these conditions at smaller time intervals, to better support operational decision-making and avoid overstating system usability. Additionally, weather factors that were omitted in this study—mist, hail, and thunderstorms—should be included to ensure understanding of expected weather impacts.
- *Further In-depth System Validation:* While this thesis explored the feasibility of a dual-hub system through expert consultation, further research is required to fully understand the integration between a drone and its docking system in real-world conditions. This includes researching technical performance, failure modes, and logistical challenges, particularly when matched with the specific drone model proposed in this study.

10.2 Addressing Effectiveness

While this study provides a constrained optimization of the drone system's trajectory design to approach this thesis' description of effectiveness, a more in-depth optimization problem framing is required to fully assess a wider interpretation of effectiveness. Future research should consider the following refinements:

- *Further Research Airside Constraints:* Explore trajectory constraining aspects currently outside of the scope of the thesis, making the OR problem framing more complex and yielding a more realistic trajectory effectiveness. Constraints could include critical airside infrastructure and airside traffic.
- *Validating Airside Operational Realism:* While the Polderbaan served as a base case for trajectory flights, its applicability to other runways must be further validated by airside operational experts. Specifically, systematic analyses should be conducted for more complex runways— Such as the Aalsmeerbaan and Buitenveldertbaan which cross each other—to ensure that trajectories remain effective under varied layout constraints and traffic scenarios.

- *Current Protocol Adjustments and Design by Kievit Engagement:* Operational experience is needed to deepen understanding of runway inspection practices. This entails interviewing Kievit operators to capture their workflows and decision-making. Incorporating their insights into protocol design, as well as their outlook on innovation, could improve the alignment of autonomous drone procedures with existing practices. As RCR is one of seven tasks an inspection vehicle does during its inspection procedure, doing RCR by drone, a significant part of a Kievit operation would be automatized, potentially making the complete runway inspections more efficient. Future research must thus develop how protocol combinations can be found.
- *Expanding to Other Runway Inspection Tasks:* As described in Section 2.2.1, the runway inspection carried out by a Kievit includes eight tasks, of which one is RCR. To further assess the effectiveness of autonomous drones—not only for RCR but for multiple—further research is required into expanding the use case for modular tasks. Modularity has been taken into account in the feasibility of drone systems, see Chapter 4, and potential benefits are discussed in Appendix E.4. An interesting initial research focus would be FOD detection simultaneous with RCR, as done currently by the Kievit operator during a runway inspection. This could be supported by integrating a camera feed payload alongside MARWIS, enabling either automated artificial intelligence-based detection or external visual confirmation of a runway debris.

10.3 Addressing Safety

Although this study provides an assessment of the drone system's risks through a HAZOP analysis, a thorough evaluation with an optionally further adapted trajectory design is required to fully encapsulate all relevant risk implications. Future research should consider the following refinements:

- *Researching Impact of Proposed Preventative Measures:* An essential part of the HAZOP analysis is identifying preventative measures for each system deviation. Future research should investigate how these proposed measures actually affect the probability and severity of those deviations. Understanding the difference these measures make will show to what extent high-risk scenarios can be mitigated. This not only strengthens the value of early-stage risk assessment but also highlights the practical safety gains of applying HAZOP in the development phase of novel systems.

- *Utilizing a Threat and Impact Analysis:* Future studies should further address threats such as spoofing and jamming attacks against the drone's navigation and communication systems. Additionally, controlled off-site collision tests—where drones are intentionally impacted into a runway—will help quantify damage expectations and drone retrieval processes. These threats can be analysed using a Threat and Impact Analysis, often done in combination with a HAZOP according to academic literature.
- *Researching Human Factors and Emergency Response Readiness:* Future research should explore how airside personnel respond to drone-related incidents or system failures, such as emergency landings or communication loss. This includes evaluating situational awareness and the ability to follow emergency procedures. Understanding these human factors is crucial for ensuring that safety protocols are not only technically sound but also operationally feasible in real-world scenarios.

10.4 Visualisation Model Extensions

With further development, data-driven visualisation has the potential to yield additional meaningful operational and safety insights on the integration of autonomous drones in the airside environment. This development requires expanding the model into a multi-agent simulation model. This section outlines several key directions for future extensions, each paired with testable hypotheses.

1. *Simulating Drone, Aircraft and Kievit Decision Making:* Introducing rule-based logic for drones, aircraft and Kievits, outside of historical data or simple drone protocol, enables analysis of realistic traffic interactions and decision-making conflicts within airside.

    - **H1: "Unexpected coordination issues and bottlenecks will emerge between drones, Kievits and aircraft."**

      Rationale: Even with rule-based decision-making, unplanned interactions are likely when agent logic intersects in operational zones.

    - **H2: Subsequent emergent behaviour between drones, Kievits, and aircraft will lead to new insights on the integration of drones in airside.**

      Rationale: Allowing each modelled agent to operate under its own logic can lead to behaviour patterns.

2. *Simulation over multiple days to a full operational year:* Extending the model time frame to cover a full year would allow the analysis of inspection frequency trends, operational bottlenecks, and seasonal traffic differences. A long-term view could validate patterns that are not visible within a single-day simulation.

    - **H3: "Runway inspections occur more frequently during off-peak seasons than during peak seasons."**

      Rationale: Lower traffic volumes during off-peak months lead to longer idle runway times, which in turn trigger more frequent drone inspections.

    - **H4: "Over the course of a full operational year, drone-based runway condition reporting will be more time-efficient than current Kievit inspections."**

      Rationale: Initial model insights show that RCR phase of Kievit inspections is more time-consuming; drones are expected to also outperform Kievits over longer periods.

3. *Integrating Weather Components:* Integrating the KNMI weather dataset allows an analysis of drone robustness under specific weather conditions throughout an operational day. This would give insights into the occurrence of weather-caused.

    - **H5: "Weather events will lead to a significant number of cancelled or affected drone inspections."**

      Rationale: Based on technical feasibility findings, wind gusts are expected to frequently exceed operational drone thresholds.

4. *Incorporating undesired event probabilities and simulating safety procedures:* Embedding probability-based triggers for undesired events over an operational year, based on HAZOP described root causes, will allow the system's emergency procedures to be validated in a simulation environment.

    - **H6: "A significant number of Return-to-Home routes will have trajectories in proximity to aircraft, indicating a potential near-miss risk."**

      Rationale: As highlighted in the risk assessment, emergency procedures like RTH may activate unpredictably during trajectory issues. Under scaled-up operations, this is expected to result in trajectories near aircraft.

A Exploratory Research

A.1 Potential Drone Use-Cases at Schiphol Airside

This initial literature review explores existing research on drone use cases and potential applications at airport airside. The use-cases are divided into three categories: *"infrastructure inspections"*, *"monitoring"* and *"case-specific flights"*. Exploring the available use cases of drones was fundamental to subsequent discussions during the internship to determine the research angle and specific case study for this thesis, according to *Stage 0* of the research design, see Chapter 3.

A.1.1 Infrastructure Inspections

Drones offer a potential use-case for infrastructure inspections, such as identifying surface irregularities that could affect take-off and landing requires measuring surface elevations and determining the Pavement Condition Index (Congress et al., 2022). Research shows that drones equipped with LiDAR and high-resolution cameras can perform regular automated scans can detect potential hazards such as external debris or rubber build-up from aircraft tyres, posing as an efficient alternative to current inspection methods (Neuvition, n.d.).

Aircraft stands are areas where personnel and travellers move to and from aircraft and where aircraft make pivoting movements, resulting in a key area requiring frequent pavement integrity inspections, such as detecting cracks and subsurface weaknesses that could compromise ground safety. This infrastructure inspection is currently done by vehicle-mounted laser scanners but has the potential for automated use with drones as researched at Schiphol *(Internal Schiphol Research, Personal Communication 25-02-2025)*

Lightning functionalities around the airport facilities are essential for safe nighttime and low-visibility operations. Research shows inspection that involves finding malfunctioning or misaligned lights that could pose a risk, drone-mounted sensors shown to be able to rapidly identify faulty bulbs and inconsistent brightness on runway edge lighting by communicating directly with pre-programmed software (Sitompul, Surya, Suhandi, & Zakaria, 2019). This use case at Schiphol has already seen operational use, and further research could be done into optimizing this integration *(Internal Schiphol Research, Personal Communication 25-02-2025).*

Aircraft Exterior Inspections are a daily, large-scale recurrence at airports, assuring the safe flight quality criteria by running through critical functionalities such as engines and landing gear for visible damage and surface wear. Drones make it possible to also do aircraft inspections outside of the hangar and notably autonomously, enabling faster pre-flight checks and post-flight maintenance planning, significantly speeding up inspections otherwise done with complicated setups inside of hangars (Yasuda, Cappabianco, Martins, & Gripp, 2022)

A.1.2 Monitoring

FOD is troublesome for airport operations as it can damage aircraft and support vehicles, with the potential to be propelled dangerously by aircraft jet engines during takeoff. At Schiphol Airport, identifying FOD on the airport grounds is done by Kievits. Drones have been shown to potentially improve these operations, with their state-of-the-art ability for autonomous scanning and object classifications, which can lead to efficient object removal by Kievits. Research shows successful detection for each of the FOD classes laid out in its study and correctly classifying each of the objects, concluding in a high potential of usability of drones for this task at airsides (Papadopoulos & Gonzalez, 2021).

Snow and Ice Management is necessary at airports as these winter occurrences impact airport operations. Monitoring the runways/taxiways and stands for snow accumulation or slippery surfaces, is necessary to determine if operations can proceed (Internal Schiphol Research, Personal Communication 25-02-2025). With the use of LIDAR sensors, measurements can be made of the height and depth of snow or ice, and this information can be obtained efficiently by attaching the sensors to a drone. Leading the airport authorities to make informed decisions regarding de-icing operations or runway closures quicker during inclement weather conditions (Neuvition, n.d.). This exploratory application is in essence what is later translated into its daily repetitive task *runway condition reporting*, not only during snow and ice management.

Wildlife Management is done at airside, by tracking and monitoring wildlife activity around the perimeter to mitigate high-risk, high-consequence incidents, such as bird-engine strikes. Using drones for wildlife hazard management at airports could provide significant benefits for the identification of hazardous wildlife species, due to the versatility and speed of drones, equipped with high-quality sensors, improving the effectiveness of wildlife hazard assessments (Mendonca & Wallace, 2021).

Security Surveillance at airports is essential for operational safety and is done by providing continuous monitoring of airport perimeter fences, restricted areas, and potential security threats. Drones with night vision and thermal capabilities have been shown to be able to detect unauthorized access and track suspicious movements. Significant progress has been made with drone usage in security surveillance: with a bird's-eye view and rapid mobility, drones have the potential to be used for security surveillance and could be beneficial in the airport environment (Mohammed & Pasam, 2020)

A.1.3 Case-Specific Flights

Logistics and delivery by drones offer efficiency within large airport environments, as they can be used to transport vehicle parts, documents, tools, and other items between locations, increasing efficiency and reducing delays. However, realizing the full potential of drone deliveries depends on challenges including no-fly zones and drone load limits (Jia, Zhang, Luo, & Wen, 2022). Delivery tasks by drone have already been trailed at Schiphol Airport *(Internal Schiphol Research, Personal Communication 25-02-2025).*

Environmental monitoring at airports is done for policy analysis and regulatory demands. Periodic drone flights can provide data for monitoring air and noise pollution around airports. For example, an environmental drone (E-drone) can ascend to a pre-determined height periodically, measuring air pollutants at that location. When multiple E-drones are deployed across different locations, custom software can generate an air quality heal index map of the region, usable for short and long-term environmental analysis (Rohi, Ejofodomi, & Ofualagba, 2020)

Construction Progress and Safety could be monitored by drones. Site-specific surveys using drones allow for progress check-ups on construction projects, without physical boundaries often present in large construction sites. Research has shown that there is also the potential to improve real-time safety monitoring, enabling on-site safety managers to effectively inspect inaccessible or potentially unsafe locations on the site (Martinez, Gheisari, & Alarcón, 2020).

Emergency Response can be aided by drones providing aerial perspectives of accidents or incidents, assisting emergency personnel in assessing the situation and planning. Additionally, drones can be used to deliver emergency equipment. The effectiveness of drone deployment for emergency mapping has been demonstrated, in academic research, whilst also highlighting the importance of prepositioned teams, regulatory preparedness, and efficient data processing to meet the demands of emergency management (Boccardo, Chiabrando, Dutto, Tonolo, & Lingua, 2015).

B Runway Inspection Specification

B.1 Runway Condition Reporting Code

Following the RCR internal Schiphol manual for RCR and the detailed interpretation of RCR by Royal Schiphol Group (2024a); TCCA GRF Implementation Team (2021), the meaning behind RCR is described as following. GRF standardizes links between the observed runway conditions and a numericalRunway Condition Code (RWYCC), formulating an expected aircraft braking action. Using the MARWIS sensor data, Airport assessors use agreed criteria to determine how slippery each third of the runway is and assign a RWYCC from 0 to 6, where 6 represents a dry runway (excellent condition) and 0 represents an extremely slippery, dangerous condition. Using the GRF, the runway is assessed in three equal portions (touchdown zone, midpoint, rollout zone). A condition code is assigned to each third if contaminants are present. For example, an airport might report a runway condition as "5/3/3", meaning the first third is code 5 (wet – good braking), and the latter two-thirds are code 3 (medium braking). RWYCC and their standardized, internal, descriptions can be seen in Tabel B.1.

Runway Condition Code (RWYCC)	Description of Runway Surface Condition
6 (Dry)	Dry runway (no contamination) – Braking action expected to be Good.
5 (Good)	Wet runway (surface visibly damp) or runway with thin water/slush ($\leq$ 3 mm) or light dry snow. Braking action Good.
4 (Medium/Good)	Runway with compacted snow or frost. Braking action expected Medium to Good.
3 (Medium)	Runway with loose wet snow or moderate depth dry snow; or slippery when wet (certain paved surfaces). Braking action Medium.
2 (Medium/Poor)	Runway with standing water ($>$3 mm) or slush, or significant wet snow. Braking action Medium to Poor (reduced braking).
1 (Poor)	Ice-covered runway (cold, dry ice). Braking action Poor.
0 (Nil)	Wet ice, or water on top of compacted snow/ice – extremely slippery. Braking action Nil (unsafe).

Table B.1: RCR Coding (Royal Schiphol Group, 2024a)

C Component Specification

C.1 Sensor System

Table C.1: Specifications of the MARWIS Sensor (Lufft, 2025)

Category	Info
Sensor	MARWIS
Manufacturer	Lufft
Measured Parameters	Road condition (dry, moist, wet, ice, snow, slush, chemically wet), Road surface temperature, Ambient temperature, Water film height up to 6mm, Dew point temperature, Relative humidity, Ice percentage, Friction (calculated)
Weight	1.7kg
Size (LxWxH)	110x200x100
Position Heigh	0.5m, 1.0m or 2.0m
Operating Temperature	-40 to 60 C
Height Error Margin	Able to deviate 10% during operation and produce usable data
Operation	100 Measurements per second
Usable Velocity Range	$<$ 200 kmh
Requirements	Powersupply: 12V DC supply, typical power usage is 10-15W, corresponds to 0.8 to 1.25 amp.

C.2 Runway Dimensions

Table C.2: Runway Dimensions (LVNL, 2024)

Code	Name	Runway (m)	Strip (m)	RESA (m)
18R/36L	Polderbaan	3800x 60	3920 x 300	240 x 120 & 240 x 120
06/24	Kaagbaan	3500 x 45	3559 x 300	240 x 90 & 90 x 90
09/27	Buitenveldertbaan	3453 x 45	3573 x 300	150 x 90 & 95 x 90
18L/36R	Aalsmereaan	3400 x 45	3520 x 300	240 x 90 & 240 x 90
18C/36C	Zwanenburgbaan	3300 x 45	3420 x 300	120 x 90 & 230 x 90
04/22	Oostbaan	2,014 x 45	2140 x 300	220 x 90 & 180 x 90

D Weather Analysis

D.1 Schiphol Weather Properties (2015-2025)

Table D.1: Schiphol Weather Data Analysis (KNMI, 2025)

Parameter	Range	Average
Daily Mean Temperature	-6,6 °C – 29,5 °C	11,41 °C
Min. Daily Mean Temperature	-10.5 °C – 21.4 C	7.56 °C
Max. Daily Mean Temperature	-4.5 °C – 36.4 °C	15.14 °C
Daily Mean Wind Speed	1 m/s – 14.6 m/s	4.89 m/s
Max. Hourly Mean Wind Speed	2 m/s – 23.0 m/s	7.39 m/s
Max. Daily Mean Wind Gust	3 m/s – 35 m/s	11.85 m/s
Daily Mean Precipitation	0 mm – 67.2mm	2.4 mm
Max. Hourly Mean Precipitation	0 mm – 26.5 mm/h	0.922 mm/h
Mean Duration of Precipitation	0h – 22.4h	1,79 h
Mean Mist Occurrence (vis $>$ 1000m)	-	8.7%

D.2 Schiphol Decadal Temperature and Precipitation (2014-2024)

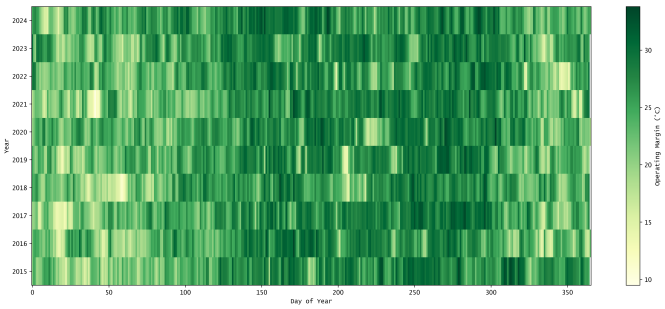


Figure D.1: Daily Temperature Operability

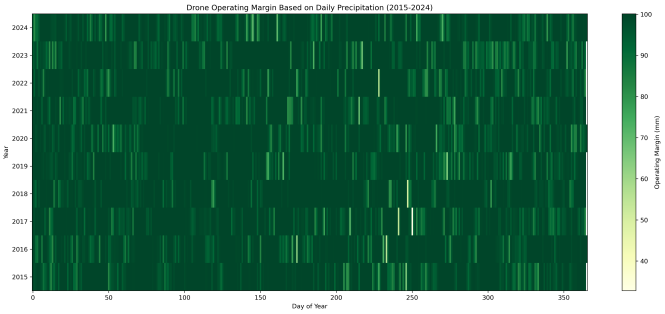


Figure D.2: Daily Precipitation Operability

E Expert Interviews

E.1 Ethical Considerations

Interviews with human participants for academic research must adhere to ethical guidelines. In this academic study, the interview protocol is reviewed by an HREC before any data collection. Key ethical considerations included:

- **Informed Consent:** Prior to each interview, informed consent was gained from each expert. Each interviewed expert got an explanation of the study's purpose, what their involvement could mean and how the study would respect anonymous reporting. It was made clear that this study would be made openly accessible in the TU Delft repository. Participants were able to ask questions on the the interview approach and discuss potential risks or benefits, as to which they could decide to voluntarily participate. To confirm the participant's decisions, consent material was presented, that emphasize that participation is completely voluntary and that the interviewee can decline to answer any question or withdraw at any time without consequence.
- **Confidentiality & Data Management:** As participants share opinions and discuss processes of their occupation, confidentiality is an important aspect of the study. Participant information is anonymized and minimized, by representing the participants by their company and not going into specifics of their function or department. Written and recorded transcripts are stored securely on the TU Delft Cloud to prevent unauthorized access. Good data management practice, as mandated by ethics committees, involves having a plan for how data will be handled: to assure this, a data management plan was submitted to the ethics committee, detailing amongst other things, that post-study transcripts would be wiped, leaving only the summary seen in this appendix. By following HREC guidelines on confidentiality and data management, the study ensures compliance with legal and ethical standards and aims at establishing a level of trust with the participants. All participants agreed to the presented measures.

By grounding the interview approach in qualitative practices and ethical standards, this thesis aims not only to ethically incorporate the participants but also to assure the credibility and integrity of the research conclusions. References to the interview summaries and interview synthesist are made throughout Chapters 4 and 5.

E.2 Interview Approach

1. **About the Experts:** All four expert interview participants are affiliated with the Schiphol Airport Infrastructure Innovation Team. P1 is a Service Owner Winter Operations and Drones at Royal Schiphol Group, bringing expertise in airport logistics and drone integration. P2 is a CTR licensed Drone pilot at the geodesy department of Koninklijk Heijmans N.V., the main contractor responsible for Schiphol Airside Infrastructure, providing practical knowledge and experience of drone uses at Schiphol Airport. P3 is a CTR licenced Drone pilot, working at Helix Aerial Vision, providing practical knowledge and experiences in conducting drone flights at Schiphol, most recently for light measurement projects. P4 is Infrastructure Inspection expert, working for Sawmwoh Innovation Centre B.V., providing practical knowledge and experience of runway infrastructure inspections at Schiphol Airport, currently employed for ongoing inspection contracts at Schiphol Airport.
2. **Approaching the Experts:** All four experts were approached during the earlier phase of the six-month internship at Schiphol Airport. All participants have had previous interactions with the

Infrastructure Innovation Team, and were willing to participate in this study. All participants were contacted by phone or in person before setting an interview date.

3. **Interview Setup:** All interviews were conducted according to a semi-structured interview setup, based on preconceived discussion topics, where the discussion is led by topic themes, but also allowing for new topic exploration (Kvale & Brinkmann, 2009). The discussion topics were the following:
   - *Drone System Exploration*
   - *Sensor System Exploration*
   - *Autonomous Drones as an Improvement*
   - *Drone Criteria Identification and Weighting*
   - *Drone Selection*
   - *Drone Weather Resilience*
4. **Data Pre and post processing:** All interviews were either recorded or transcribed live with the participants' consent, in compliance with ethical considerations as described in Section E.1. The recorded audio files were manually transcribed to ensure accuracy and completeness. After transcription, the interviews were analysed to identify key themes and insights. These synthesized findings were then integrated into the thesis, forming the validation for the feasibility analysis and trajectory design. Summaries of each interview are presented in the following sections, highlighting the most relevant expert perspectives. A synthesis of the four interviews can be found at Appendix E.4.

E.3 Interview Summaries

E.3.1 Heijmans Infrastructure

02-04-2025
1h
The following interview was held at the offices of Koninklijk Heijmans B.V. in Dordrecht, South-Holland.

Interviewer: I.R. Hall
Interviewee: P2/Heij

Summary

[α1] Criteria Identification: The expert discussed aspects relevant to Schiphol Airport, and all discussed aspects were incorporated in the pre-interview identified criteria, thereby strengthening their inclusion in the weighted decision matrix.

[α2] Criteria Weighting: After agreeing on the list of criteria, the expert was asked to compare their weight and hierarchy of importance in the Schiphol environment. The expert considered accuracy the most relevant, which aligns with the pre-identified criteria, followed by wind as the secondary factor. Payload capacity was deemed less important since all identified drones are capable of carrying significant payload weights, making it a non-issue according to the expert. Battery capacity was considered less crucial as the maximum route of 3.6 km falls within the battery range of all potential drones. Temperature, wind resistance, and water resistance were rated accurately. Flight speed was rated higher than initially identified, the expert noted that in an emergency, a drone's ability to quickly reach a safe height and remove itself from the situation as fast as possible could significantly reduce risk.

[α3] Drone Identification and Selection: The expert deemed the identified list of drones as complete for the flight objective. The M350RTK was identified as the most versatile and suitable drone for Schiphol RCR, motivated by its compactness and an ability to carry various payloads, including high-resolution cameras, LiDAR systems, and the MARWIS sensor, proving superior in specifications regarding modularity and flight accuracy compared to other drone options. The integration of DJI's gimbal and camera systems enhances its modular usability. The mentioned M350RTK flexibility makes it the preferred choice for both routine and specialized tasks according to the expert.

[α4] Water and Wind Effects on Drone and Sensor: Water resistance, does not significantly affect drone flight capabilities according to the expert, but could impact sensor equipment by causing water droplets on the lenses. The expert noted that maximum wind resistance serves as a safety assurance, allowing consistent flight even in stronger winds. However, the system would automatically trigger a RTH during autonomous flights in bad weather. This means that a threshold increase is required to result in a higher percentage of operable days.

[α5] Possible Sensor Data Corruption: An essential discussion point was the MARWIS sensor data accuracy when positioned at a height of 2 meters, as the propeller's airflow might affect the measured accuracy of the asphalt and impact the generated RCR codes. *This meant that the research objective might be compromised, requiring crucial further research.*

[α6] Payload Energy and GPS from Drone: The expert confirmed that payloads, including the MARWIS sensor, can utilize the power supply of M350RTK. The drone itself uses internal LTE and GNSS for navigation and is designed to share these functionalities with its payload.

[α7] Autonomous Drones vs. Pilot-Driven Drones: According to the expert, autonomous drones are increasingly used for repetitive inspection tasks in all fields, particularly in controlled environments with consistent parameters. In the United States, autonomous flight for infrastructure inspection is more common, while Dutch CTR regulation limit such operations. The expert noted that autonomous flight is highly suitable for routine tasks, reducing the need for a pilot and minimizing human involvement in repetitive jobs. The expert emphasized the potential of autonomous flight for consistent trajectories, especially in applications like the Rotterdam harbour, where drone usage is an industry frontrunner.

[α8] Automated Drone Charging and Hub Efficiency: Drones designed to automatically dock and charge within a hub are consistently used across industries; the expert describes systems where the drone lands in a designated spot within the hub, which then automatically secures the drone by its legs and starts charging protocols. These hubs vary in size, capabilities and manufacturers, with DJI hubs being known for robustness and reliability in harsh environments. The concept of automated charging is essential for continuous operations, especially in challenging locations like airports, and could be readily used in this researched trajectory.

[α9] Dual Hub Setup: The dual hub setup, where a drone can start and land from two different hubs, is not commonly seen in practice according to the expert. Typically, the industry standard involves one hub per drone, where the drone takes off, performs its task, and returns to the same hub. The expert has not encountered a functional dual hub system in the field, suggesting that it may not be widely used or standardized in the industry. Dual Hubs at Schiphol airport would be placed not by Heijmans but by an external company and operated by Schiphol Operations for RCR and potentially by Heijmans for additional infrastructure inspections.

[α10] Overriding DJI Technology and Programming Challenges: Modifying DJI drones to bypass factory settings, such as reducing the minimum safe flying height, is complex according to the expert: although technically possible with custom software, DJI generally does not support such changes. Implementing these modifications would require the expertise of a DJI partner. This highlights the challenge of using modified drones for specific tasks while maintaining official support.

[α11] Flight Trajectories and geofences: The expert mentioned that RTK function of the M350RTK ensures highly accurate flight, supported by LTE and GNSS for waypoint navigation. Flights follow designated geofences, typically divided into green, orange, and red zones, preventing the drone from leaving the predefined area and triggering RTH or kill switch if necessary. Flying at a height of 2 meters, particularly for the MARWIS sensor, poses challenges when the drone moves horizontally, risking collisions with low-lying obstacles. Trajectories would require flight repeaters to maintain a stable signal over long distances, as the length of the runway exceeds the standard 2.4 GHz signal range of approximately 2.5 km.

[α12] Overall Feasibility and Innovation Outlook: The expert described autonomous drone integration at Schiphol Airport as a logical development, one that will probably be functional in the near future. However, the expert described that certain inspections, such as asphalt assessment, in which P2 is experienced, will not soon benefit from the autonomous functionalities, as the task is ad hoc and occasional. The expert does see the logic of the innovative developments in the repetitive trajectory operations and is of the opinion that the technology is near feasible in the current technological climate.

E.3.2 Samwoh Innovation Centre B.V.

03-04-2025
0.5h
The following interview was held online.

Interviewer: I.R. Hall
Interviewee: P4/Si

Summary

[β_1] **Real-Time Processing Challenges:** According to the expert current drone systems suffer from significant post-processing delays, lacking the real-time data analysis needed for immediate runway inspections and decision-making. The expert's view on the future of using drones for infrastructure inspections relies on the development of real-time identification, and can not coexist without co-development. Drone technology is deemed a goldmine concept that has not yet delivered results and in the foreseeable future will not overtake the complex tasks required for inspection and monitoring at airports. Post-processing is pointed out as a real issue for automating current inspection tasks, seen across the industry and a big problem for airports wanting fast results.

[β_2]**Multi-Tasking Capabilities and Efficiency:** Current inspections by Kievits can perform multiple tasks simultaneously—such as conducting FOD detection alongside runway inspections—-an ability that drone systems have not done in practice according to the expert. Integrating additional inspection functions into a drone's trajectory would require robust real-time processing, a capability that the expert doubts is currently feasible or not close to being practical. Additionally, the expert deemed drones to have a considerably lower efficiency compared to Kieivits. While a Kieviet can inspect an area in about five minutes, a drone is expected by the expert to requires around ten minutes to deploy before it can even start its inspection, resulting in slower overall performance.

[β4] Weather Resilience: It is mentioned that Kievits are able to reliably perform runway inspections in all weather conditions. In contrast, the inspection expert states that drones are just not consistent enough in his industry to be a direct competitor, as they are more vulnerable to adverse weather, making them a less dependable option for inspections in challenging environmental conditions.

[β5] Inspection Technology: Additional systems for infrastructure inspections are discussed, for possible modular capabilities of a drone, which align more with the inspection tasks typically executed by P4; Using drones, the areal aspect combining LiDAR could generate efficient high-resolution point cloud data, offering a more accurate assessment than methods relying solely on photographs from ground level.

[β6] Sensor Integration Issues: Advanced sensors, such as the MARWIS sensor, are difficult to integrate into drones, as it is less rigid than traditional inspection methods. The drone flight would make it difficult to handle sensitive data on which decisions will be made. The expert further discusses difficulties and does not see adaption as an easy feat.

[β7] Autonomous Operation Potential: Although autonomous drone operations for runway inspections are not common at present, there is potential for future trials, particularly in regions like Hong Kong where autonomous technologies are being explored at a higher level according to the expert. As an expert visiting many Asian airports, there is definitely an autonomous future of airport technology including drones, but so far there are no practical and consistent autonomous drones seen on the airside.

[β8] Overall Feasibility and Innovation Outlook: The expert discussed the near future of drone implementation at airports, and a trend he often sees is that the promises can not be made true. His reasoning behind this is that airports are such complex systems that introducing new technology is difficult and less practical than current expert methods, due to technology not developing at the speed wanted.

E.3.3 Helix Aerial Vision

04-04-2025
0.5h
The following Interview was held online.

Interviewer: I.R. Hall
Interviewee: P3/Hav

Summary

[γ1] Criteria Identification and Weighting: When asked about drone operation criteria at Schiphol Airport, the expert highlighted that wind and rain tolerance are the most critical factors, as heavy conditions can affect drone stability and performance. The expert does mention that in very serious conditions, drone flights, in general, will not happen at the airside, due to general safety concerns. Flight Accuracy is deemed an important criterion, and utilizing GPS and RTK technology can ensure precise navigation and execution of predetermined flight paths, guaranteeing safety and effective data collection. Flight Speed is deemed less important as operations are limited by the functionalities of sensor systems. The expert mentions that the flight speed criteria are dependent on the combination of payload weight and drone capacity, and therefore are also relevant criteria.

[γ2] Evaluation of Drone Models and Alternatives: When assessing suitable drone models for infrastructure inspections, the expert noted several key considerations: acknowledging that larger drones like the Freefly offer robust performance but are very large and heavy with flight capabilities of just 12 minutes with the payload. Older models such as the M600 might be less optimal due to limited flight times and outdated technology. When asked for additional drones missing on the shortlist, the expert mentioned fixed-wing drones with vertical take-off capabilities, as a potential alternative for covering longer runway distances. This type has reduced manoeuvrability compared to quadcopters, which complicates a dual-hub landing system. This insight underscores the need to align the drone's capabilities with specific trajectory design, ensuring that the selected system can deliver both high performance and compatibility for the runway environment. M350RTK is selected by the expert as the optimal system and is deemed reliable for RCR trajectory and an industry frontrunner.

[γ3] Dual Hub Setup: The expert confirmed that a setup using two drone hubs is feasible and already in use, citing a recent project he worked on with another specialist in the Netherlands experienced with installing and operating dual drone hubs and integrating AI systems. According to the expert, the approach offers benefits for rapid and flexible deployment and promising inspection efficiency and operational capability.

[γ4] Possible data sensor corruption: When discussing the flight trajectory and drone-sensor setup, the expert addressed concerns regarding sensor data collection during low-altitude flights. He noted that while the drone can safely fly at that height, challenges may arise from downforce such as dust getting in the way of the sensor, potentially reducing data accuracy. However, P3 indicated that these issues can be managed through proper sensor placement and calibration.

[γ5] Drone Stability and Wind Tolerance: The expert confirmed that M350RTK maintains stability at around 10 meters per second making it very capable of collecting data with the MARWIS sensor. Capabilities under challenging wind conditions are discussed, and mentioned that the drone is reliable for the Schiphol environment: the manufacturer's specifications state a wind resistance of 12 m/s, real-world experience of P3 suggests that the drone can handle higher wind speeds, and the drone's design offers a comfortable margin. This performance reliability ensures that even if conditions slightly exceed standard limits, the drone can still maintain its course and provide accurate data during inspection tasks.

[γ6] Integration of the MARWIS Sensor into Drone Systems: Integration of the MARWIS sensor with M350RTK is both practical and straightforward. The expert explained that the sensor can be connected to the drone's energy system using multiple USB-C ports. Additionally, by using software development kits, operators can implement further software modifications to enhance functionality. This setup enables the sensor to collect and transmit real-time data effectively during flight, allowing inspection and monitoring tasks. The successful combination of hardware and software demonstrates the sensor's compatibility with current drone platforms.

[γ7] FOD Detection with Real-Time Inspection: Drones as an improvement over current Kievits is discussed, and the M350RTK capability to additionally identify FOD using additional payloads, critical for maintaining runway safety. Possibility for real-time inspections is discussed, the expert explained that current drone-in-a-box systems already support live video feeds, which facilitate real-time monitoring and is currently at a very high standard and usable for the discussed trajectory. Although minor transmission delays, such as a one-second lag, can occur, these do not significantly impact the overall effectiveness of the system according to the expert. By integrating real-time footage, operators could execute runway inspections alongside the MARWIS sensor from service roads, portraying a complete alternative to current Kievit tasks.

[γ8] Overall Feasibility and Innovation Outlook: The expert's overall outlook on drone integration for runway inspections is positive, emphasizing that the benefits outweigh the challenges. P3 stresses that despite some technical hurdles—such as managing sensor accuracy at low altitudes and adjusting for environmental conditions—the technology progression is undeniable, necessary and beneficial in the long run. Continuous innovation and proactive collaboration among technology providers and operational teams are essential, as is a forward-thinking approach, for future developments of an airport airside.

E.3.4 Royal Schiphol Group

29-04-2025
1h
The following interview was held at the offices of Royal Schiphol Group in Amsterdam, North-Holland

Interviewer: I.R. Hall
Interviewee: P1/Sch

Summary

[δ1] Dual Hub Setup: It was suggested by P1 that a single hub configuration, where the drone departs and returns to the same hub, may offer operational advantages, compared to the initially designed dual-hub setup. A single-hub setup would increase sensor data collected per mission as it would fly over the length twice, and avoid the complexities introduced by dual landing and coordination requirements. This would result in a longer flight time and require more battery life.

[δ2] Hub Placement: Regarding hub placement at the Polderbaan, it was recommended that the left-hand drone hub side would be better placed on the opposite side of the runway. This adjustment would avoid requiring drones to cross active taxiways, where parked aircraft might be present during RCR procedures. Reducing the need to overfly aircraft minimizes potential operational and safety risks.

[δ3] Possible Data Sensor Corruption: When discussing potential data corruption caused by drone wind downforce as mentioned in preceding interviews, it was pointed out by P1 that only the air humidity measurement of the MARWIS sensor might be affected. These measurements rely on atmospheric sampling, which could be disturbed by propeller turbulence. However, the key measurements for RCR, such as water pooling and ice presence are captured by infrared sensors at very high speeds, making them unlikely to be impacted at all. P1 emphasized that although no immediate critical issues are expected, further dedicated research should validate this assumption for completeness.

[δ4] Drone Stability for RCR: Concerns regarding drone flight stability affecting sensor data were addressed by stating that minor drone movements during operation, according to M350RTK specifications, would not significantly impact the MARWIS data quality. It was indicated that calibration procedures and drone flight precision are sufficient for the intended data collection.

[δ5] Integration of MARWIS Sensor into Drone System: Attention was drawn to potential challenges related to battery capacity when integrating the MARWIS sensor. The sensor's 12V energy requirement could place additional strain on the drone's power system, potentially reducing the achievable flight time during a trajectory.

[δ6] RCR Specification for Schiphol and Real-Time Inspectionl: It was outlined that Schiphol's RCR operations adhere to ICAO guidelines, which emphasize the need for expert judgement when assessing runway conditions. Even if drone systems were to enhance data collection speed and quality, human oversight remains necessary to officially validate and finalize the condition report. This responsibility is mentioned to be potentially performed remotely, but operational practices at Schiphol include additional tasks during runway openings that necessitate a physical human presence. Following this, P1 explained that at Schiphol, and particularly at the Polderbaan, specific RCR time intervals must be maintained throughout operational hours, requiring frequent reassessments due to the continuous opening and closing of the runway.

[δ7] Overall Feasibility and Outlook: The integration of autonomous drones for RCR operations is seen by P1 as a valuable enhancement to the overall runway opening process. Although human presence remains a legal and operational necessity, automating part of the operation has the potential to improve efficiency and reduce inspection time. Specifically at the Polderbaan, the applicability was deemed useful, as it lies far away and has less impacting runway constraints. The use of autonomous drones was seen as a practical and meaningful improvement within the broader goal of enhancing airside operational workflows at Schiphol Airport.

Table E.4: Royal Schiphol Group Interview

E.4 Interview Synthesis

E.4.1 Explanation

The purpose of a synthesis is to bring together the individual expert perspectives in a structured way, highlighting where they agree, where they diverge, and how their insights collectively support and validate the technical feasibility analysis and trajectory development. By systematically comparing each interview against the pre-identified interview topics, this approach tries to ensure no critical viewpoint is overlooked and that conclusions rest on a balanced industry experience.

E.4.2 Drone System Insights

The expert insights of P2/Heij, see E.3.1, P3/Hav, see E.3.3 and P1/Sch, see E.3.4 on the designed drone system reveal both converging and diverging perspectives. Both P2/Heij and P3/Hav affirm that integrating the MARWIS sensor with the M350RTK is practical and technically robust. According to their evaluations, the sensor can be connected via USB-C ports and programmed through the available SDK, allowing MARWIS data collection as well as real-time data collection and effective inspection tasks. P1/Sch offers insight into the impacts of the 12V energy supply of the MARWIS sensor and adds to the integration that this might impact battery life and thus usability.

P2/Heij describes challenges associated with overriding DJI factory settings to modify operational parameters. While technically achievable with custom software, these modifications require the assistance of specialized DJI partners. P3/Hav complemented this view by commenting that this modification is feasible and happens a lot in the drone industry. Both experts agree that automated drone charging systems are feasible and critical for repetitive operations, they ensure that drones can reliably dock, recharge and thereby support efficient operational workflows.

However, a notable difference arises in the discussion on the dual hub setup. P2/Heij points out that a dual hub configuration is not commonly observed in industry practice; P2/Heij emphasizes that the standard approach typically involves a single hub from which the drone takes off and finally returns. P1/Schip compliments this approach by suggesting that a one-hub trajectory would benefit the mission, doubling sensor data collected and simplifying the hub setup, yet decreasing the efficiency of the trajectory). In contrast, P3/Hav confirms that dual hub setups are not only feasible but have already been implemented in recent projects, highlighting that such systems can offer inspection efficiency, especially when integrated with AI for advanced operational capabilities.

Overall, the synthesis suggests that while the current drone design vis sound, the dual hub configuration presents promising opportunities but is not convincingly deemed superior, requiring further research and development.

E.4.3 Sensor Data Collection Insights

The expert insights of P2/Heij, see E.3.1, P3/Hav, see E.3.3 and P4/Si, see E.3.2 on sensor data collection highlight several challenges and improvements concerning data accuracy and real-time processing. P2/Heij raises concerns about possible data corruption when the MARWIS is mounted at the required low flight altitude, noting that propeller downwash may affect RCR data accuracy——a critical factor that could compromise the research objective. On a similar note, P3/Hav acknowledges the risks associated with low-altitude flights, such as dust interference due to downforce, but emphasizes that these issues mitigation tactics such as careful sensor placement and proper calibration should be researched. P1/Sch contradicts P2/Heij and P3/Hav, see E.3.4 by stating that the infrared sensor of MARWIS is fast enough that sensor data will not be corrupted, whilst also mentioning that air density, not measured by infrared, will be affected.

With regard to real-time monitoring alongside RCR data collection, P4/Si points out the broader challenge of real-time data processing; current drone systems experience significant post-processing delays, which hinder decision-making streams, suggesting that without advancements in real-time identification technology, the full potential of drones remains unrealized, particularly given the complex nature of airport operations. P3/Hav offers a more optimistic perspective by highlighting the integration of real-time video feeds in modern drone-in-a-box systems, mentioning that while minor transmission delays can occur, these systems already provide high-end capabilities that, when combined with sensor data, offer a viable and efficient alternative to manual Kievit inspections. P1/Sch mitigates the worry of P4/Si, as real-time monitoring is not yet deemed necessary in the current airside environment, as protocol requires personnel presence for additional runway-opening tasks anyway.

Together, these insights underscore the need for further research into both sensor data accuracy during drone downwash effect and the effectiveness of infrared, as well as research into the development of real-time processing capabilities to fully harness the potential of drone technology for further automation of airside.

E.4.4 Autonomous Drones as an Improvement Insights

The expert's insights of P2/Heij, see E.3.1, P3/Hav, see E.3.3 and P4/Si, see E.3.2 provide a nuanced view on the potential of autonomous drones with regard to current operations. P2/Heij emphasizes that autonomous drones are particularly well-suited for repetitive inspections in controlled environments, where autonomous flight is valuable for reducing human involvement and ensuring consistent trajectories—an approach that P2/Heij backs up with use cases at Rotterdam Harbour. P4/Si, however, highlights the limitations of current drone systems compared to current RCR vehicles, which can perform multiple tasks simultaneously, mentioning that drones have not yet achieved similar multi-tasking capabilities usable for an Airport environment. According to P4/Si, integrating additional functions into a drone's trajectory would demand robust real-time processing, while also stressing that although the potential for autonomous drone operations exists their efficiency remains lower than that of existing systems. In contrast, P3/Hav has a more effective view on drone deployment gained from drone flight experience, envisioning that with further technological advancements, drones will be able to conduct autonomous inspections continuously, ultimately enhancing overall operations. P1/Sch gives a more practical operations-oriented insight on what the set-up has to offer; improving part of the process but not mitigating current Kievit procedures: utilizing drones mitigates a large part of the RCR process, the data collection, which is an improvement, but doesn't overrule the task as a whole.

Together, these insights suggest that while autonomous drones hold significant potential for improving routine inspections and reducing human workload, key challenges——such as multi-tasking limitations and slower deployment times compared to traditional systems—must be overcome and trialled to fully realize proven benefits at airside.

E.4.5 Criteria Identification and Weighting Insights

The expert insights of P2/Heij, see E.3.1 and P3/Hav, see E.3.3 confirm that the pre-interview criteria for evaluating drone operations at Schiphol Airport are complete and aligned with operational demands. P2/Heij highlighted that the key aspects relevant to Schiphol, such as accuracy, wind resistance, temperature, and water resistance, were captured in the initial criteria. When both experts were given the criteria without weighting, P2/Heij deemed accuracy the most critical factor, with wind conditions following and payload capacity and battery life, are of lesser importance than pre-identified due to the sufficient capabilities of current drone models and the relatively short distance. Notably, P2/Heij pointed out that flight speed, while generally less critical during standard inspections, becomes more important in emergency scenarios where rapid altitude gain is crucial for safety.

P3/Hav provided a runway-focused perspective by underscoring that wind and rain tolerance are the most important factors, as they can directly impact drone stability, whilst flight accuracy is paramount, with GPS and RTK technologies ensuring precise navigation along predetermined flight paths. Although regarding flight speed as less significant due to the sensor system's limitations and the low likelihood of emergency returns under routine operations, he acknowledged that the interplay between flight speed, payload weight, and drone capacity still needs consideration.

In conclusion, the synthesis of expert insights confirms that no additional criteria need to be added or existing criteria removed. However, adjustments to the values weights have been made to better reflect operational priorities at Schiphol. Specifically, flight accuracy remains rated 5, flight speed has been increased from 2 to 3, payload capacity reduced from 4 to 2, and battery life has been decreased from 3 to 2. Operating Temperature (1), Wind resistance (4) and Water resistance (3) remained the same. After modification, DJI Matrice 600 PRO and DJI Matrice 350RTK performed better and DJI Matrice 300RTK and Freefly Alta X performed consistently, resulting in the same selection of DJI Matrice 350RTK, aligned with the expert's pick.

E.4.6 Drone Selection Insights

The expert insights of P2/Heij, see E.3.1 and P3/Hav, see E.3.3 converge on the M350RTK as the optimal drone for Schiphol RCRoperations in the current market. P2/Heij confirmed that the identified list of drones is complete and highlighted that the M350RTK stands out for its versatility, compact design, and superior modularity. Its capacity to carry diverse payloads ensures high flight accuracy and effective performance. The integration of DJI's gimbal and camera systems further enhances its modular usability, supporting both routine inspections and specialized tasks. Additionally, its capabilities to provide GPS support and efficient charging render it particularly well-suited for the operational requirements at Schiphol.

In evaluating alternatives, P3/Hav noted that while larger drones like the Freefly can offer robust performance, they are less favourable due to their heavy build and limited flight duration under the required payload conditions. Older models such as the M600 were also deemed suboptimal because of outdated technology and restricted flight times. Although fixed-wing drones with vertical take-off capabilities were mentioned as potential options for covering longer runway distances, their reduced manoeuvrability complicates the implementation of a dual hub landing system and thus falls outside of the objective's scope. These considerations reinforce the M350RTK's status as the industry frontrunner and the most compatible choice for the intended trajectory and operational environment at Schiphol Airport.

E.4.7 Drone Weather Resilience Insights

The expert insights of P2/Heij, see E.3.1 and P3/Hav, see E.3.3 present complementary perspectives on weather resilience. P2/Heij explains that while water resistance does not significantly impact the drone's flight capabilities, it can affect sensor performance due to water droplets on the lenses, highlighting that wind resistance serves as a safety buffer, with the system automatically triggering RTH in adverse conditions. P3/Hav reinforces the robustness of the M350RTK by confirming that it maintains stability at wind speeds of around 15 m/s, even though manufacturer specifications rate it for 12 m/s. P3/Hav's real-world experience suggests that the drone can perform reliably even when

conditions slightly exceed these limits, ensuring accurate sensor data collection during inspections. This enhanced wind tolerance, combined with potential threshold adjustments, indicates a promising avenue for increasing the number of operable days.

P4/Si however, brings a cautionary perspective, see E.3.2, emphasizing that despite the technological advancements, drones remain more vulnerable to adverse weather compared to Kievits, which consistently perform runway inspections under all weather conditions. According to P4/Si, this vulnerability makes drones less dependable in challenging environments, noting that, until further technological improvements are realized, conventional vehicles are likely to remain the preferred choice for critical inspections during weather occurrences.

Together, these insights show that while the M350RTK shows promising weather resilience, especially in terms of wind tolerance, the current limitations of drone technology in handling adverse weather conditions cannot be overlooked. These perspectives serve as a reminder of the existing reliability gap between drones and Kievits, emphasizing the need for continued advancements and trailing to identify and bridge this gap.

E.4.8 Overall feasibility outlook

The experts paint a picture of technically feasible drone operation, that requires phased adoption rather than an immediate adoption. P2/Heij sees automated drone integration as a logical next step for routine trajectory operations——technology that is nearly mature—yet doubts its near-term benefit for specialized tasks like asphalt assessment and is sceptical about dual-hub configurations until further development makes them practical. P4/Si offers a cautionary counterpoint, arguing that airports are such complex systems that many early promises around drones remain unfulfilled; technology has not advanced quickly enough to supplant established expert methods. P3/Hv provides a more optimistic long-term perspective, emphasizing that despite technical hurdles, efficiency potential justifies sustained investment, provided there is continuous innovation and close collaboration between technology providers and airport operators. P1/Sch brings a pragmatic operational outlook: while human presence remains legally and operationally binding for tasks such as lighting checks and wildlife management during runway openings, drones can accelerate a significant part of runway opening protocols, by increasing the efficiency of data collection at a far away lying runway as the Polderbaan.

F Airside Constraints

F.1 OLS and ILS Zones

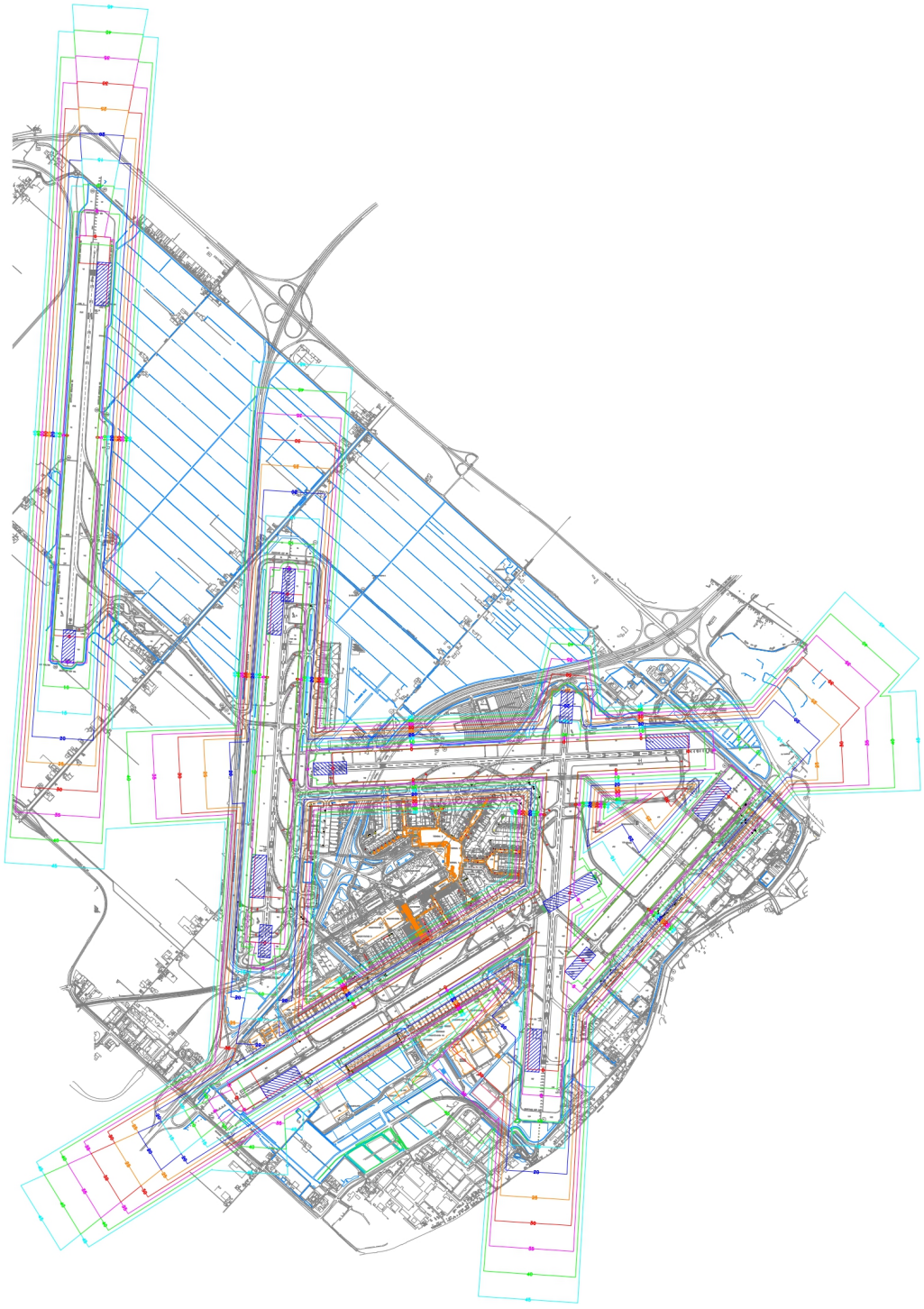


Figure F.1: Schiphol OLS and ILS Zones (Royal Schiphol Group, 2023)

G Hub Placements

G.1 Zwanenburgbaan

The Zwanenburgbaan has additional runway constraints: it has two ILS systems with accompanying critical areas which need to be worked around. This dual ILS system allows the runway to host arriving aircraft from both directions. Additionally, due to the area in which the Zwanenburgbaan is positioned, the drone hubs are subject to extra placement constraints.

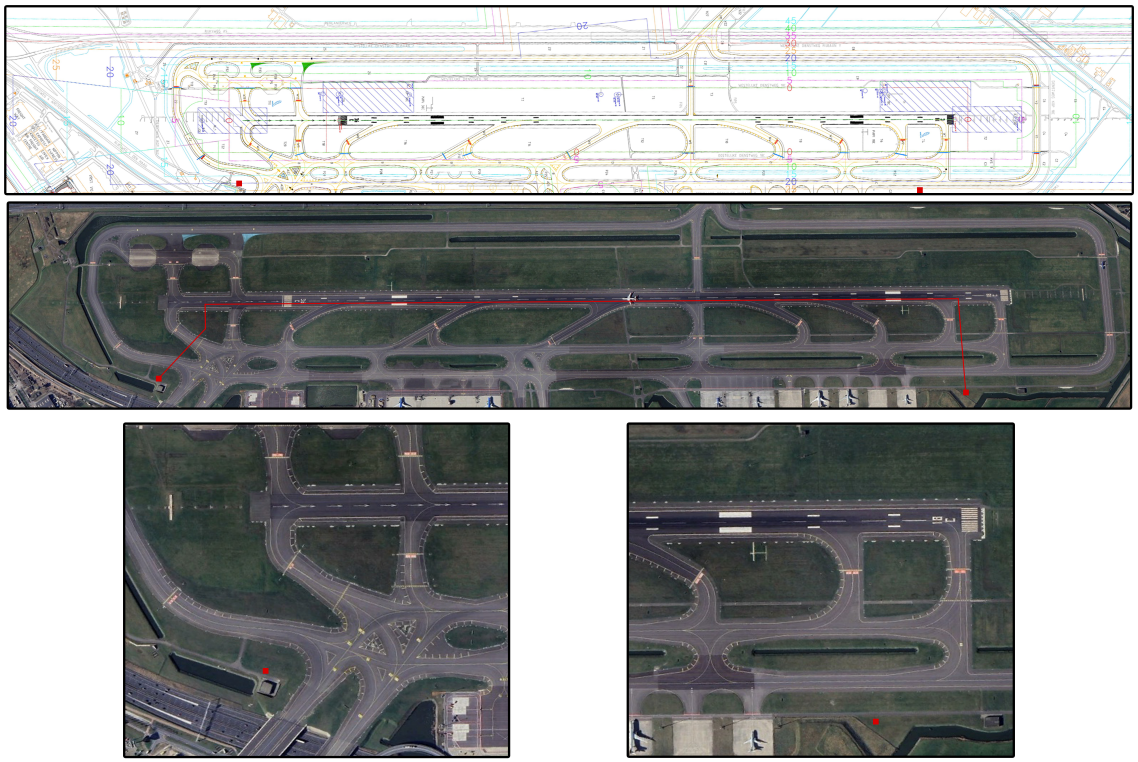


Figure G.1: Hub Placement Zwanenburgbaan (Google LLC, 2025; Royal Schiphol Group, 2023)

G.2 Buitenveldertbaan

The Buitenveldertbaan crosses over the Aalsmeerbaan, complicating flight trajectory execution, and has drone hubs positioned on opposite sides of the runway due to the critical area and multiple taxiways at the centre of Schiphol Airport.

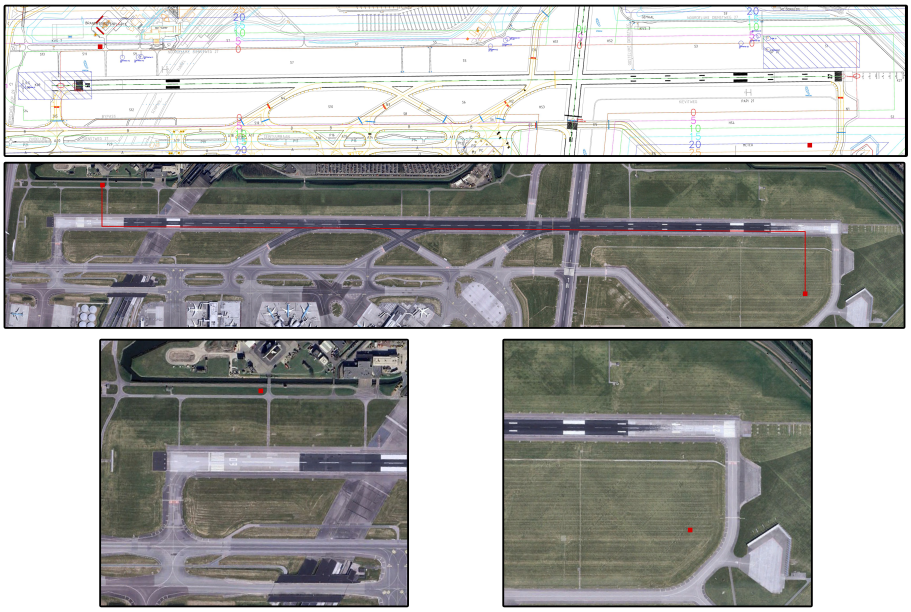


Figure G.2: Hub Placement Buitenveldertbaan (Google LLC, 2025; Royal Schiphol Group, 2023)

G.3 Aalsmeerbaan

The Aalsmeerbaan crosses over the Buitenveldertbaan, and basses the end of the Kaagbaan closely, resulting in crossing two different ILS zones, and potentially complicating trajectory execution.

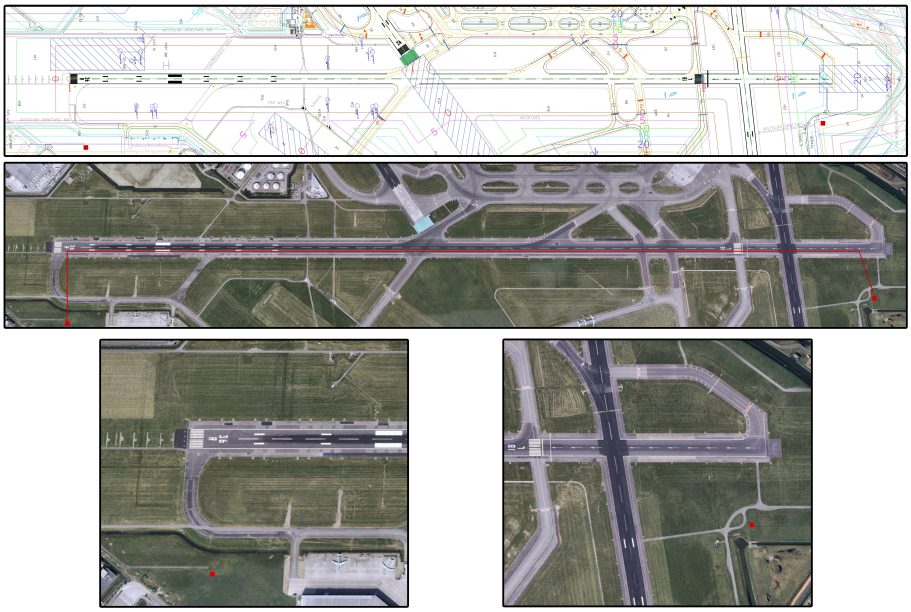


Figure G.3: Hub Placement Aalsmeerbaan (Google LLC, 2025; Royal Schiphol Group, 2023)

G.4 Kaagbaan

The Kaagbaan specific constraints made hub complicated hub placement: whilst trying to minimize crossing taxiways as much as possible, the drone requires to fly over less runway, additionally the drone hub is placed in a higher risk area due to the limited operational possibilities.

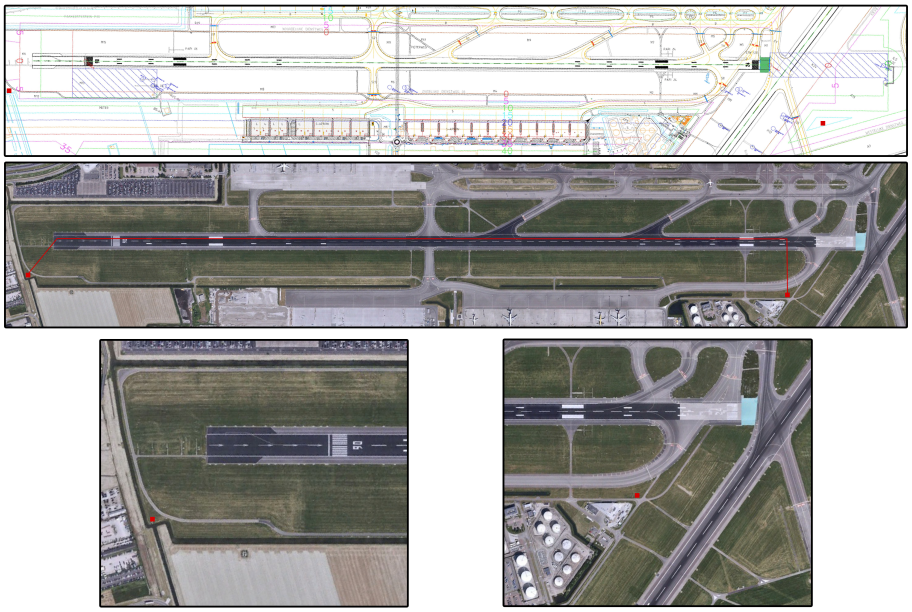


Figure G.4: Hub Placement Kaagbaan (Google LLC, 2025; Royal Schiphol Group, 2023)

G.5 Oostbaan

The Oostbaan is the shortest runway, but hosts ILS critical area, resulting in the drone trajectory having to cross over more taxiways than desired.

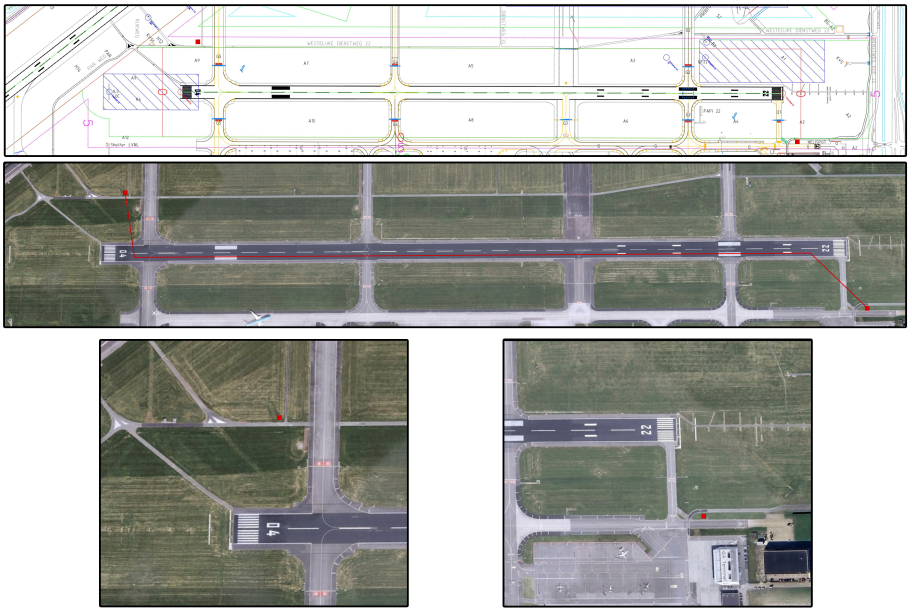


Figure G.5: Hub Placement Oostbaan (Google LLC, 2025; Royal Schiphol Group, 2023)

H HAZOP Preparation

H.1 HAZOP Prerequisites

Before executing a HAZOP study, an understanding amongst participants of the relevant system documentation is required for efficient and accurate risk identification. Drawing on Rausand's framework (Rausand, 2011), the described required prerequisites are mentioned in bold, followed by their origin tailored to this study, originating from Chapters 4 and 5. These prerequisites were shared with the participants before the safety meeting.

- **Process Flow Diagram:** Required for a complete system understanding, in this study describing how the drone trajectory processes follow each other, provided in Figure 5.3 and Figure 5.5.
- **Process Equipment:** Detailed information on technical requirements for the process operability, including information on the drone system and sensor, provided in Chapter 4.
- **Layout plans:** Required for an understanding of the to-be-analysed process. In this study that involves the trajectory design and hub placement, giving context to the system and the risks associated, provided by 5.2
- **Provisional Operating Instructions:** Draft procedures on how the system is executed, which is relevant for understanding risks and is described in the protocol flow diagram, provided by Figure 5.5.
- **Operating Ranges:** Specifications on equipment ranges, according to weather, speed, internal batteries and temperatures. These are provided in Chapter 4 and the resulting constraints discussed in Chapter 5 determined by the scope of the study.
- **Emergency shut-down procedures:** Information on how the system's internal safety procedures work, and how hazards are dealt with to give the process the required details, discussed in the discussion of relevant CAS systems and emergency procedures, provided in Chapter 5.

H.2 Setup Safety Meeting

1. **Introduction:** Introducing each participant, sharing expertise and general discussion outlooks.
2. **Description of the HAZOP approach:** Discussing how the study is executed.
3. **Presentation of System and Operation:** Discussing provided pre-requisites, presenting the overall system and processes which will be analysed in the study and discussing possible questions that arose
4. **Worksheet presentation:** Node is introduced and elaborated
5. **Establishing Evaluation Metrics:** Establishing coherent evaluation metrics with which the risks identified will be evaluated during and after the meeting.
6. **Analysation:** Node is discussed, agreed upon, consequences discussed and including the other steps, see Appendix H.3.
7. **Conclusion:** Per node all parameters are concluded per worksheet
8. **Repetition:** Repeat steps 4, 5 and 6 for all Nodes
9. **Summary and Discussion:** Summary of findings and their general meaning, followed by concluding the safety meeting.

H.3 Worksheet Setup

For each node in the process, a dedicated worksheet is used to capture, in a structured way, all credible deviations from the design intent along with their causes, consequences, existing safeguards and recommended follow-up actions in accordance with the technique discussed by (Rausand, 2011). The worksheet columns are defined as follows:

1. **Ref. no.:** A unique identifier for each deviation entry on the worksheet.
2. **Parameter:** The relevant parameter for the condition deviating from the design intent.
3. **Guidewords:** A short prompt is applied to each parameter to systematically generate plausible deviations. See H.1 for all guidewords used.
4. **Deviation:** The actual departure from the design intent, is formed by combining the guideword and the parameter.
5. **Possible causes:** All credible reasons why the deviation might occur
6. **Consequences:** The safety hazards or operability issues that would arise if the deviation actually occurred.
7. **Safeguards**: Existing measures that either prevent the deviation from happening or limit its consequences.
8. **Comments:** Impacts on the operation for which the drone is being used.
9. **Actions recommended:** Follow-up action if the deviation would occur.
10. **Actions allocation:** The department responsible for the follow-up action if the deviation would occur

H.4 Guidewords

In adherence with best practices described by (Crawley et al., 2008, p.16), the guidewords used in the worksheets, see Appendix J, can be seen in Table H.1.

Table H.1: Guidewords and their generic meaning

Guidewords	Meaning
No (not, none)	None of the design intent is achieved
More (More of, higher)	Quantitative increase in a parameter
Less	Quantitative decrease of a parameter
Other than	Different value of parameter combination

I HAZOP Summaries

I.1 Safety Meeting

22-05-2025
2.5h
The following safety meeting was conducted online, in collaboration with Schiphol Airport and Luchtvekeersleiding Nederland, and set up together with the Safety department of Schiphol Airport

Team Leader: I.R. Hall
Team Members: I.R. Hall, P1, P2, P3, P4, P5

Summary

The meeting opened with introductions of each participant sharing their background, and positions in their company. Royal Schiphol Group attendees included two safety advisors—each possessing expertise in airside safety—alongside a flow-management operations specialist—working in day-to-day airside operations—–an airside service-owner representative–whose insights into routine inspection responsibilities informed discussions of drone applicability. Representing LVNL was an operational risk manager, with an external view on drone use at Schiphol Airport, and experienced in developing drone use policy and risk assessment.

Following this an introduction was given to the study, introducing the goal, the current RCR baseline and the need for development, including a live demonstration of the autonomous-drone proof-of-concept simulation model. The various roles of the participants in this system were discussed including highlighting their interoperability. Process ownership per step was clarified: in autonomous runway opening inspections LVNL expects a clean and operable runway, prompting FMA to start the opening process when demanded, according to a service system provided by the service owner. In this setup, the general risk visions were described, where LVNL's risk priorities differed from Schiphol: LVNL is primarily concerned with preventing collisions. In their internal drone risk research, LVNL focuses especially on take-off and landing phases where high relative speeds could result in catastrophic windshield impacts. Although no registered incidents exist worldwide, internal tests have underscored the severity of these hazards. Conversely, Schiphol places greater emphasis on the broader operational consequences of drone incursions—such as unplanned runway closures or traffic disruptions—as well as broader safety implications on airside personnel. Together these two visions give a nuanced view of the hazard and operability research.

Starting of the trajectory discussion, the group started by examining the prospective role of autonomous drones in RCR. The debate centred on whether drones would ultimately supplant the existing Kievit inspection vehicle or operate simultaneously; the prevailing view was that full autonomy represents the long-term objective. Regulatory considerations followed: although flights at 2 m altitude already fall under established vehicle regulations, the defining challenge lies in governing the drone's autonomous trajectory. LVNLs regulatory vision of this strongly differed, by seeing drones strictly as aircraft. The choice of runway was subject to opinions on a significant risk exposure. The Polderbaan runway's relative isolation minimizes drone–aircraft interactions as it does not near other runways. A discussion point was the differentiation of drone near aircraft occurrences; in the inner ring of the CTR there is no further classification, exposing an underdevelopment. Next, the team established uniform risk-evaluation metrics, assigning severity ratings to potential process failures, which can be seen in Section 6.5.2, and was crucial for post-processing of the results.

The discussion then progressed through each phase of the planned flight path, according to HAZOP meeting set up. Taxiway crossings emerged as a critical concern in phase 1: to prevent unsupervised overflight of active taxiways the route was rerouted around the ILS from the north, following the meeting iteratively improved in Chapter 5. During phase 2, bird strikes were identified as causing multiple problems: on one side the drone could hit birds unintentionally, but birds also mentioned to be known to attack drones. The most significant vulnerability covering all phases, but denoted in phase 2 was the deviation of control integrity, due to GPS spoofing and signal jamming. Such incidents—potentially occurring unintentionally through nearby electronic interference—could induce a zero-rate event and require runway closure. LVNL regard this in their current practices as more relevant for aircraft but do highlight the large risk this could have on drones in their CTR. Additionally, all parties agreed upon communications and control protocol requirements to be explicitly safeguarded against interference with the ILS. Finally, emergency landing procedures were deemed excessively risky. A consistent RTH procedure is deemed more reasonable. It was stressed by the safety advisors that well-function emergency procedures are most critical for safe drone operations and that their function mitigates most problems, thus highlighting the potential for their malfunctioning as highly impactful as seen in the risk evaluation.

Finally after concluding the HAZOP worksheets, there was the occasion to discuss further visions on the risks and process hazards: Thorough operator qualifications and trial executions are demanded for further innovation development. Focus was put on the management of tasks, who is responsible for the drone before flight (infrastructure), who is responsible during, and who retrieves the drone in emergency landings. It was urged that there were many difficulties, in particular by the participants from FMA, before implementations were possible, but essentially this does not disregard research of the possibilities. LVNL emphasized the critical distinction between beyond-visual-line-of-sight and visual-line-of-sight operations, which was a serious safety concern before attending the safety meeting. Because the proposed drone flights are conducted at just 2 m above ground level, they fall within visual-line-of-sight parameters and can be continuously monitored from the west airside control tower, ensuring an improvement in the realm of regulatory acceptability.

Flyaways are deemed highly unlikely in LVNL's risk analysis, and established follow-up procedures are designed to reorganize operations locally rather than impose full runway closures. As a result, LVNL considers its current protocols sufficient, while recognizing the need for continued refinement as drone operations evolve. Potential safety improvements offered by drones were highlighted, particularly in mitigating the hazards introduced by Kievit inspection vehicles traversing runway intersections, with lower speeds and physical contact with the runway itself. Drones thus are deemed potentially beneficial for these inspections though difficult in the regulatory body.

For further refinement of probability aspects, it was deemed critical to contact an expert in drone technology, for which a subsequent meeting was planned for the following day. Additionally, a subsequent meeting with LVNL drone representative was planned for review, as with the safety advisor for subsequent evaluation steps and discussion.

I.2 Review Meetings

26-05-2025
2h
The following four 30 minute meetings were held in individually in consecutive order during one day.

Review Leader I.R. Hall
Review Members: I.R. Hall, R1, R2, R3, R4

Summary
R1 "Reviewing drone deviation probabilities.":
During the meeting with the drone expert, all identified drone system deviations were reviewed. Jamming is deemed to require highly specific targeting—making it a greater concern, since it represents deliberate interference rather than accidental. Many deviations are classified as severity 2: they remain possible but are very unlikely to occur. Minor horizontal drifts under strong wind conditions are rated with higher severity 4 but are not likely to be system faults. Landing, docking, and related manoeuvrers carry an unlikely severity rating, with only a handful of incidents expected per year. RTH procedures have proven reliability through widespread operational use; EL procedures carry moderate severity but remain very usable. To further reduce risk, dedicated pre-programmed landing areas are recommended. Overall a consensus was found with the probabilities throughout the worksheet study. It was further discussed that over the past ten years, drone systems have evolved significantly—failures are now almost non-existent, making this technology highly promising for aviation integration. When issues do arise, they are often attributable to pilot error rather than system faults. The platform continues to advance with new use cases and capability layers under development, consistently performing well within those emerging scenarios.

R2: "Reviewing sensor deviation probabilities."
During the meeting, the various sensor deviations mentioned in the worksheets were assessed. First, the sensor calibration was discussed and how regular recalibration is required, whilst still deeming calibration faults probable due to the unstable nature of a drone system, which is less consistent than the vehicle for which it was designed. The acceptability margin of 10% was discussed and thus the data quality should rather be intact and that deviation probability would require a rare influx to the trajectory. Geotagging accuracy malfunctions are deemed improbable but are described as malfunctions as the sensor capabilities are not designed for drone system use yet. Further discussion points were the 20 per cent angle of the sensor and possible consequences to prices and the speed at which the drone should fly, to impact the measurement rate, for Schiphol it was deemed that up to 100km/h is feasible for good results, reevaluating the constraints for the trajectory.

R3: "Reviewing consequence severities and regulation.":
During the meeting GPS spoofing and signal jamming were discussed as critical hazards that could lead to complete loss of drone navigation and position awareness, followed up by the high-consequence risk of a drone–aircraft collision and the current difficulty in reliably detecting and mitigating deviations in real-time. It was mentioned that the most dangerous intrusion scenarios arise when the drone is moving near aircraft in take-off, where engine collisions could have the largest impacts. Other consequences were structurally iterated through to find disagreements with the reviewer. Required regulatory adoptions were discussed to enable safe, recurring drone-based runway inspections. It was mentioned that the most probable regulatory adaption involves the framework allowing Schiphol to declare and control temporary segregated airspace—legally assigning responsibility for opening and closing that airspace. Bypassing LVNL's existing CTR limits oversight can be bypassed during inspection windows. This regulatory adaption requires legal amendments with support from IenW, and is deemed a more feasible regulatory adaption than the other option: re-framing what drones are seen as, removing their VFR status and thus changing their position as a whole in controlled airspace.

R4: "Reviewing overall HAZOP study.":
In collaboration with the Safety Advisor who assisted in organising the safety meeting at Schiphol Airport, a complete review of the HAZOP study was conducted—its worksheets, findings, and acknowledged limitations. During this session, the most significant risks were highlighted and a consensus was reached on the study's final conclusions. The review confirmed that the documentation reflected the meeting discussions and that all critical points were addressed. One key improvement identified was the need for a clearer demarcation of responsibilities for each system consequence: ASM is responsible for the drone asset and their supporting hubs assets; whenever a drone malfunction, requires maintenance, or needs relocation, ASM carries out the necessary actions. The Service Owner governs system usage and sets policy—issuing formal work orders to ASM whenever changes are required— this is an explicit distinction between the principal, who defines the requirements, and ASM, who implements them. FMA handles all on-site operational tasks: in the event of an incident, the FMA coordinates the response, authorizes any runway openings, and liaises directly with the Kievit team. FMA's authority and responsibilities apply strictly during their active duty period, ensuring that each operational shift has clear accountability. LVNL is responsible for requesting a runway and carries no further responsibilities in the execution of the runway inspection, in the current regulatory framework.

J HAZOP Worksheets

Study Title	HAZOP Autonomous RCR Drone Trajectory									
Reference Pre Req N	S1, S2	[P2] Pre Mission						Date	23/04/2025	
HAZOP Team Memb	LR. Hall, P1, P2, P3, P4, P5							Meeting Date	22/05/2025	
Node Discussed:	[N1] Pre-Launch Check									
Design intent:	Before take-off, the drone is verified for it battery state, sensor state and GPS state, which are all as expected, clearing the drone for trajectory execution.									
No.	Parameter	Guideword	Deviation	Probability (1-4	Possible Causes	Consequences	Severity (1-4	Safeguards	Comments	Actions recommended	Action allocated to
1-1:1	Battery Charge	Less	Battery charge is less than intented	4	Chargingport not attached properly, dronehub missing external energy source	Trajectory is not expected to be able to be completed, pre mission cancelled	1	Redudant battery, redudant energy source dronehub	Runway requires inspection by Kievit, runway opening less efficient but not delayed.	Drone hub requires maintenenance.	FMA is responsible for the runway not opening on time, will contact SO, who will contact infrasturcure for the malfunctioning drone hub.
1-2:1	Sensor Ready	No	MARWIS sensor not reporting as ready for runway inspection	4	MARWIS sensor not present or not attached properly	RC data can not be collected; pre mission cancelled	1	Frequent sensor checks	Runway requires inspection by Kievit, runway opening less efficient but not delayed.	MARWIS sensor requires maintenenance.	FMA is responsible for the runway not opening on time, who will contact SO responsible for MARWIS data assurance
1-2:2		Other than	MARWIS sensor reporting as ready for runway inspection, but is not ready	3	MARWIS sensor internal system not working as designed; faulty wiring	RC data can not be collected, pre mission should be cancelled but is not, resulting in no sensor data	2	Frequent sensor checks	Runway requires inspection by Kievit, but only after drone has completed its trajectory, resulting in delayed opening.	MARWIS sensor requires maintenenance.	FMA is responsible for the runway not opening on time, who will contact SO responsible for MARWIS data assurance
1-3:1	GPS Lock	No	No GPS connection	3	GPS antenna unplugged; satellite blackout; jamming	No position reference; geofence prevents take-off; pre-mission cancelled	1	Frequent drone gps status check	Runway requires inspection by Kievit, runway opening less efficient but not delayed. Drone	GPS system requires maintenenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
1-3:2		Less	GPS accuracy worse than required	3	Clouded weather; RTK correction loss; faulty antenna, spoofing	Potential position drift; potential geofence breach; wrong launch location, pre-mission cancelled	1	Frequent drone gps status check	Runway requires inspection by Kievit, runway opening less efficient but not delayed. Drone	GPS system requires maintenenance	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance

Figure J.1: N1 Worksheet: Pre-Launch Check

Study Title	HAZOP Autonomous RCR Drone Trajectory			
Reference Drawing No.		Phase	[P2] Pre Mission	Date	23/04/2025
HAZOP Team Member:	I.R. Hall, P1, P2, P3, P4, P5			Meeting Date	22/05/2025
Node Discussed:	[N2] Launch Execution				
Design intent:	When a runway inspection is required, the drone is triggered, before executing its taxi route.				

No.	Parameter	Guideword	Deviation	Probability (1-5)	Possible Causes	Consequences	Severity (1-5)	Safeguards	Comments	Actions recommended	Action allocated to
2-1-1	Mission Trigger	None	Trigger is not issued when trajectory is meant to start	1	Misinformed communication from LVNL, internal drone system failure.	Drone pre-mission does not commence, runway condition is not reported. Pre mission cancelled	1	Frequent Drone checkups	Runway requires inspection by Kievit, runway opening less efficient but not delayed.	Drone hub requires maintenenance	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone. Communication with LVNL to find cause of mistake.
2-1-2		Other than	Trigger is issued when trajectory is not meant to start	2	Misinformed communication from LVNL, internal drone system mistake.	Controlled drone flight in an uncontrolled airspace or above an active runway, could lead to severe consequences for surrounding vehicles or aircrafts	4	Dual trigger confirmation before trajectory initiation	Drone executes trajectory but at the wrong time: runway could be in use. As the trajectory control is not compromised, a zero rate is not necessary, but the runway closes down immediately	Drone hub requires maintenenance, communication channels with LVNL need to be reevaluated	LVNL is responsible for giving the trigger to FMA, who is in turn responsible for starting the process. If trigger is drone hub mistake, SO takes responsibility.

Figure J.2: N2 Worksheet: Launch Execution

Study Title	HAZOP Autonomous RCR Drone Trajectory								
Reference Drawing No		[P2] Pre Mission				Date	23/04/2025		
HAZOP Team Members	L.R. Hall, P1, P2, P3, P4, P5					Meeting Date	22/05/2025		
Node Discussed:	[N3] Taxiing execution								
Design intent:	Drone traverses taxing corridor at set height to arrive at target location								
No.	Parameter	Guideword	Deviation	Probability (1-5)	Possible Causes	Consequences	Severity (1-5)	Safeguards	Comments	Actions recommended	Action allocated to
3-1:1	Altitude	More	Drone executes trajectory above planned altitude	2	Internal drone calibration error, GPS error, jamming, lift off effect/wind updraft	Drone enters uncontrolled airspace, could interfere with OLS zones, RTH procedure commences, trajectory not completed	2	High altitude geofence, tighten drone calibration intervals	Runway requires inspection by Kievit, but only after drone has completed its RTH, resulting in delayed opening	Run through Drone internal system, Run through hardware functioning	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance
3-1:2		Less	Drone executes trajectory beneath planned altitude	2	Internal Drone calibration error, GPS error, jamming, wind downdraft	Drone enters dangerous altitude, erratic behavion, could collide with ground, RTH procedure commences, trajectory not completed	2	Low altitude geofence (1m; could influence effectiveness flight). tighten drone calibration intervals	Runway requires inspection by Kievit, but only after drone has completed its RTH, resulting in delayed opening, possible drone retrieval outside of runway	Run through Drone internal system, Run through hardware functioning	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance, if there is a premature landing kievit must do retrieval.
3-2:1	Arrival Location	Other than	(Minor) Drone arrives at wrong starting point but claims to be at correct starting point.	2	Internal Drone calibration error, spoofing	Trajectory executed starts but will record in preceise sensor data	1	RTK GPS innrovement repeaters along taxi	Runway inspection is completed, but data requires additional attention for RWYCC generation as GPS location is slightly off.	Recalibrate Drone and Hub Systems	FMA responsible for data intepretation, if re run of sensor data is required SO will be held responsible for initating maintenance steps for the drone.
3-2:2		Other than	(Major) Drone arrives at faulty starting point but claims to be at correct starting point	2	Internal Drone calibration error, spoofing	Mission starts but drone will fly in a wrong direction and could trigger RTH or EL , therefore RTH is initiated	2	RTK GPS innrovement repeaters along taxi	Runway requires inspection by Kievit, but only after drone has completed its RTH, resulting in delayed opening	Recalibrate Drone and Hub Systems	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance, if there is a premature landing kievit must do retrieval.

Figure J.3: N3 Worksheet: Taxiing Execution

Study Title	HAZOP Autonomous RCR Drone Trajectory			Date	23/04/2025
Reference Drawing No.	Phase	[P2] Mission		Meeting Date	22/05/2025
HAZOP Team Member:	I.R. Hall, P2, P3, P4 and P5				
Node Discussed:	[N4] Flight Execution				
Design Intent:	The Drone traverses the trajectory flight route at target altitude and velocity, following guided waypoints for precise positional accuracy, maintaining a stable and continuous flight making the data-collection possible in its designed free airspace.				

No.	Parameter	Guideword	Deviation	Probability (1-5)	Possible Causes	Consequences	Severity (1-5)	Safeguards	Comments on operation	Actions recommended	Action allocated to
4-1:1	Altitude	More	Drone executes trajectory above planned altitude	2	Internal drone calibration error, GPS error, jamming, lift off effect/wind updraft	Drone enters uncontrolled airspace, could enter OLS zones, possible interfering with aircraft flight, RTH procedure commences, trajectory not completed	2	High altitude geofence, tighten drone calibration intervals	Runway requires inspection by Kievit, but only after drone has completed its RTH, resulting in delayed opening	Run through Drone internal system, Run through hardware functioning	Runway not opening on time, who will contact SO responsible for the drone performance
4-1:2		Less	Drone executes trajectory below planned altitude	2	Internal drone calibration error, GPS error, jamming, wind downdraft	Drone enters dangerous altitude, erratic behaviour, could collide with ground, emergency landing procedure commences, trajectory not completed, high chance of ground collision	3	Low altitude geofence (1m; could influence effectiveness flight), tighten drone calibration intervals	Runway requires inspection by Kievit, but only after drone has completed its emergency landing, resulting in delayed opening	Run through Drone internal system, Run through hardware functioning	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance
4-1:3		None	During trajectory drone loses altitude completely	3	Drone internal system failure, hard wind downforce	Drone is not able to correct flight, crashlanding on runway	4	Structured collision protocol (motor shutdown),	Runway requires inspection by Kievit, but only after drone has removed drone and debris.	Run through Drone internal system, Run through hardware functioning	FMA is responsible for the runway not opening on time, who will contact SO LVNL is responsible for assuring free airspace.
4-2:1	Velocity	More	Drone executes trajectory faster than intended.	2	Internal drone calibration error, tailwind gust	Sensor data blur due, excessive battery drain, overshoot waypoints, unsifficient data	2	Improved speed controller in drone system, max speed limits, tailwind speed reduction protocols.	Runway requires inspection by Kievit, but only after drone has completed its trajectory, resulting in delayed opening.	Run through Drone internal system.	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance
4-2:2		Less	Drone executes trakectory slower than intended.	2	Internal drone calibration error, headwind gust, battery sag	Possible operational delay, battery depleated more than intended	1	Improved speed controller in drone system, min speed limits, headwind speed increase protocols.	Runway inspection will be slower than expected, but not delayed, kievit not required to do runway inspection.	Drone requires maintenance	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance
4-3:1	Horizontal Positioning	Other than	(Minor) Drone remains in green zone, but not along intended trajectory,	4	Internal drone calibration error, GPS error, spoofing, slight Side-wind, slight Wind-gusts	Corrupted sensor data, asphalt partially not sensored but runway markings not representitive for the RCR	1	GPS improvement; redudant waypoint programming	Could effect quality and efficiency of RCR, requires extra RYWCC formulation steps but doesn't require inspection by Kievit.	Run through Drone internal system, Run through hardware functioning	Runway not opening on time, who will contact SO responsible for the drone performance
4-3:2		Other than	(Minor) Drone enters orange zone	3	Internal drone calibration error, GPS error, spoofing, medium Side-wind, medium Wind-gusts	RTH procedure commences, trajectory not completed	2	GPS improvement; optimal RTH procedure to prevent disruption	Runway requires inspection by Kievit, but only after drone has completed its RTH, resulting in delayed opening, Drone internal computer must be reevaluated	Run through Drone internal system, Run through hardware functioning	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance
4-3:3		Other than	(Major) Drone enters red zone	2	Internal drone calibration error, GPS error, spoofing, strong Side-wind, strong Wind-gusts	Drone could enter ILS or OLS zone, Emergency landing procedure comment, trajectory not ocmpleted	3	GPS improvement; optimal EL procedure and retrieval procedure to prevent disruption. Redudant spoofing protection	Runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening. Drone internal computer must be reevaluated	Run through Drone internal system, Run through hardware functioning	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance
4-4:1	Battery charge	Less	Drone battery charge is lower than intended	2	Aging battery cells reducing capacity, cold temperatures, high current draw due to headwind	RTH procedure commences, trajectory not completed	2	Real-time voltage & current monitoring, low-battery pre-alarm, battery temperature sensor	Runway inspection could take longer than expected, or runway requires inspection by Kievit, but only after drone has completed its RTH, resulting in delayed opening	Drone requires maintenance	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance
4-5:1	Free airspace	Not	Designated trajectory airspace is not free	4	Bird or aircraft presence in controlled airspace and CAS malfunctions	Drone collides with contaminated airspace object, runway is completely shutdown and aircrafts rerouted trajectory not completed and debris on runway.	4	Structrually check CAS system, assure birds are no in proximity to dronehubs or runway.	Runway requires inspection by Kievit, but only after drone has removed drone and debris.	Run through Drone CAS system.	FMA is responsible for the runway not opening on time, LVNL is responsible for assuring free airspace.

Figure J.4: N4 Worksheet: Flight Execution

Study Title		HAZOP Autonomous RCR Drone Trajectory							23/04/2025
Reference Drawing No.			Phase	[P2] Mission		Date			
HAZOP Team Members		LR, Hall, P1, P2, P3, P4, P5				Meeting Date			22/05/2025
Node Discussed:		[N5] Data Collection							
Design Intent:		MARWIS sensor collects calibrated runway condition data when mission starts, usable for setting up a runway condition report with the correct GPS stamp and according to ICAO standards.							
No.	Parameter	Guideword	Deviation	Probability (1-5)	Possible Causes	Consequences	Severity (1-5)	Safeguards	Comments	Actions recommended	Action allocated to
5-1:1	Sensor Calibration	Other than	MARIWS sensor calibrated with wrong offset	4	Calibration outdated, calibration wrong.	Trajectory completed but RC data not usable; systematic bias in data, runway misclassification,	2	Dual verification protocol before takeoff; periodic calibration check	Runway requires inspection by Kievit, but only after drone has completed its trajectory, resulting in delayed opening	Sensor requires recalibration or maintenance	FMA is responsible for the runway not opening on time, who will contact SO responsible for MARWIS data assurance
5-2:1	Measurement Rate	Less	MARWIS sensor collects data at lower frequency than inteded	4	Sampling interval misconfigured; reduces samples per meter, sensor damaged	Trajectory completed but RC data might not be usable; spatial data gaps, incomplete coverage, potential undetected runway hazards	1	Sampling-rate monitor and pre warning	Could effect RC data quantity, requires extra RYWCC formulation steps but doesn't require inspection by Kievit.	Sensor requires recalibration or maintenance	FMA is responsible for the runway not opening on time, who will contact SO responsible for MARWIS data assurance
5-3:1	Data Quality	Less	☒MARWIS sensor data has a signal-to-noise ratio lower than intended	5	Dirty optics; excessive vibration; sensor aging	Trajectory completed but RC data less than optimal;	1	Periodic lens cleaning; vibration isolations	RC data less usable than desired, but no further inspection by kievit required	Drone requires maintenance for possible vibration, sensor needs maintenance	FMA is responsible for the runway not opening on time, who will contact SO responsible for MARWIS data assurance
5-3:2		Other than	☒MARWIS sensor data reports false positives or false negatives	2	Sensor Internal failure or glare or reflected sunlight,	Trajectory completed, but RC data wrong; misclassification of contamination, operational delay	2	Plausibility checks post mission by human evaluation; for early detection	Runway requires inspection by Kievit, but only after drone has completed its trajectory, resulting in delayed opening	Run through sensor internal system, possible requires maintenance	FMA is responsible for the runway not opening on time, who will contact SO responsible for MARWIS data assurance
5-4:1	Geotagging Accuracy	Late	☒MARWIS sensor data timestamps lag behind actual acquisition	3	Internal drone-sensor communication fault	Trajectory completed but sensor data less than optimal: data misaligned to map incorrect segment assignment; hinders correlation with runway thirds	1	Periodic GPS time sync; onboard timestamp validation improvement	Requires good data interpretation, but would still be usable.	Run through drone internal system, may require maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
5-4:1		Other than	MARWIS sensor data points tagged with incorrect coordinates	2	GPS error, spoofing	Trajectory completed but RC data wrong; No clear conclusion can be made on the runway state, oeprational delay	2	internal GPS system, playsability checks post by human evaluation; for early detection.	Runway requires inspection by Kievit, but only after drone has completed its trajectory, resulting in delayed opening	Run through drone internal system, may require maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance

Figure J.5: N5 Worksheet: Data Collection

Study Title	HAZOP Autonomous RCR Drone Trajectory								
Reference Drawing No			[P2] Mission				Date		23/04/2025
HAZOP Team Members	I.R. Hall, P1, P2, P3, P4, P5						Meeting Date		22/05/2025
Node Discussed:	[N6] Communication and Control								
Design Intent:	During the mission phase, the drone is flying in a high risk area, a communication signal and control integrity is present at all times, making it possible to know exactly what is going on during the trajectory and override flight protocol if necessar								
No.	Parameter	Guideword	Deviation	Probability (1-5)	Possible Causes	Consequences	Severity (1-5)	Safeguards	Comments	Actions recommended	Action allocated to
6-1:1	Signal Strength	None	Control center completely loses communication link with drone	2	Internal drone system failure, antenna disconnect;	Loss of situational awareness, of operators and LVNL, "uncontrolled" drone but still controlled via its programming, emergency landing procedure commences, trajectory not completed.	3	Redudant onboard connection backups, sound RTH triggering system.	Runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening	Run through Drone internal system connectivy, requires maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
6-1:2		Less	Control center has troubled communication link with drone	3	Aircraft signal interference; misaligned antenna;	Control prompts delayed, flight information lagging, partially uncontrolled drift	3	Continuously monitor signal quality and alert operator; hold position or slow down until link recovers	Runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening	Run through Drone internal system connectivy, requires maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
6-2:1	Control Integrity	None	Controlcenter loses all control of drone and no communication	2	accidental or non accidental jamming, system failure	uncontrolled drift or ground collission, emergency landing can not commence.	5	Properprocedure for automatic safe-landing on total link loss; onboard flight mode to keep drone level in hover	uncontrolled drone in uncontrolled airspace, zerorate is given, drone must first be removed from flight, before subsequent runway inspections.	Run through drone internal system, requires maintenance, run through system resilience, requires advancement	FMA is responsible for the runway not opening on time, LVNL is responsible for assuring free airspace.
6-2:2		Less	Control link degraded to communication only, no control options.	3	accidental or non accidental jamming, delayed emergency , system failure	Outdated situational view, no spacial awareness; commands; risk of collision or corridor breach,	4	Propper protection for weak signal, redudant connections	Must trace jamming origin, could effect airside widerscale. Runway requires inspection by Kievit, but only after drone has completed its emergency landing and retrieved, resulting in delayed opening	Drone requires maintenance	FMA is responsible for the runway not opening on time, LVNL is responsible for assuring free airspace.
6-3:2		Other than	Drone accepts commands from an unauthorized source	3	Non accidental Spoofing, or hacking	Controlled by external party, possible runway intrusion or ground collission, emegency landing can not commence	5	Introduce redudant manual override possibilities	Drone thinks it is in another place, might fly erradically, zero state given, drone must be removed	Run through Drone internal systems resilience, requires advancement	FMA is responsible for the runway not opening on time, LVNL is responsible for assuring free airspace.

Figure J.6: N6 Worksheet: Communication and Control

Study Title	HAZOP Autonomous RCR Drone Trajectory								
Reference Drawing No		Phase	[P2] Mission			Date	23/04/2025		
HAZOP Team Members	L.R. Hall, P1, P2, P3, P4, P5					Meeting Date	22/05/2025		
Node Discussed:	[N7] Emergency RTH								
Design intent:	When a RTH is triggered, the drone will fly to the closest drone hub via the shortest runway criteria unobstructed route, with a set RTH altitude								
No.	Parameter	Guideword	Deviation	Probability (1-5)	Possible Causes	Consequences	Severity (1-5)	Safeguards	Comments	Actions recommended	Action allocated to
7-1:1	RTH Trigger	None	RTH does not initiate when required	3	Internal drone system error, ad hoc geo cage modification error	Drone continues unsafe flight, high chance on collision in unsafe airspace. Emergency landing initated	3	Redudant triggering mechanism (dubble trigger route), force override protocol	Drone is not triggered, meaning unsafe triggering reason prolongs, runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening	Run through drone internal systems for error origin, drone requires Maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
7-1:2		Other than	Drone RTH initiates when not required	2	Internal drone system error, ad hoc geo cage modification error	Unnecessary mission abort incomplete data; delay runway opening retrieval operations; potential conflicts with ATC	2	Trigger confirmation delay (e.g. 3 s); dual-condition check (link + battery) before activation; Human RTH verification	Drone does RTH, RCR not completed, requiring kievit to do runway inspection, delaying opening.	Run through drone internal systems for error origin, drone requires Maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
7-2:1	Navigation Path	None	Drone can not find closest drone hub to to return to during RTH	2	Internal drone calibration error, GPS error	Drone proceeds to emergency landing	3	prefix drone hub in internal system, thoroughly test system	Runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening	Run through drone internal systems for error origin, drone requires Maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
7-2:2		Other than	Drone does not move according to RTH protocol and approved corridor	2	Internal drone calibration error, GPS error, jamming	Drone proceeds to emergency landing	3	Corridor geofence with auto-correct to centerline; real-time path-deviation alarm to operations, strict override procedures	Runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening	Run through drone internal systems for error origin, drone requires Maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
7-3:1	RTH Altitude	Less	Drone executes RTH below planned altitude	2	Internal drone calibration error, GPS error, jamming, wind downupdraft	Drone enters uncontrolled airspace, could enter OLS zones, possible interfering with aircraft flight, RTH procedure commences, trajectory not completed	3	Low-altitude geofence at RTH minimum;	Runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening	Run through Drone internal system, Run through hardware functioning	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
7-3:2		More	Drone executes RTH above planned altitude	2	Internal drone calibration error, GPS error, jamming, wind updraft	Drone enters dangerous altitude, erratic behavion, could collide with ground, emergency landing procedure commences, trajectory not	3	High-altitude geofence at RTH maximum	Runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening	Run through Drone internal system, Run through hardware functioning	FMA is responsible for the runway opening on time, will contact SO responsible for the drone performance

Figure J.7: N7 Worksheet: Emergency RTH

Study Title	HAZOP Autonomous RCR Drone Trajectory								
Reference Drawing No		Phase	[P2] Mission				Date		23/04/2025
HAZOP Team Members	L.R. Hall, P2, P3, P4 and P5						Meeting Date		22/05/2025
Node Discussed:	[N8] Emergency Landing								
Design intent:	When an emergency Landing is triggered, the drone will start landing protocols on its given location, to prevent further hazard escalation, with the desgined speed and according the desgined shutdown sequence								
No.	Parameter	Guideword	Deviation	Probability (1-5	Possible Causes	Consequences	Severity (1-5	Safeguards	Comments	Actions recommende	Action allocated to
8-1:1	Emergency Landing Trigger	None	Drone emergency landing procedure does not commence when required	3	Internal drone system error, ad hoc geo cage modification	Drone continues uncontrolled flight could lead to crash or runway incursion	5	Reduadant triggering mechanism (dubble trigger route), force override protocol	Uncontrolled drone in unctonrolled airspace, zerorate is given, drone must first be removed from flight	Run through drone internal systems for error origin, drone requires maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
8-1:2		Other than	Drone emergency landing procedure commence when not required	2	Internal drone system error, ad hoc geo cage modification	Trajectory not completed unnecessarily	3	Trigger confirmation delay (e.g. 3 s); dual-condition check (link + battery) before activation'; Human EL verification	Runway requires inspection by Kievit, but only after drone has completed its emergency landing and being retrieved, resulting in delayed opening	Run through drone internal systems for error origin, drone requires maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
8-2:1	Descent speed	less	Drone descends to emergency landing location slower than intended	2	Low battery, updraft	Prolonged in a dangerous situation	3	Improved decent controller in drone system,	Extends drone retrieval time, delays kievit runway inspection	Run through drone internal system and hardware, requires maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
8-2:2		more	Drone descends to emergency landing location faster than intended	2	low battery, downdraft	Hard landing, potential crash with runway	4	Improved decent controller in drone system,	Could lead to crash landing, resulting in closure of runway, before Kievit has to do runway inspection, large opertional delays	Run through drone	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
8-3:1	Shutdown Sequence	Not	Motors do not disarm after touchdown	2	Ground-contact sensor failure; latch bug	Possible damage, making retrieval more difficult due to debris	3	Auto-disarm on contact; motor-kill override	Runway requires inspection by Kievit, but only after drone has completed its emergency landing which takes longer due to the deviation, resulting in delayed opening	Drone requiers maintenance	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance

Figure J.8: N8 Worksheet: Emergency Landing

Study Title	HAZOP Drone trajectory									
Reference Drawing No.	S1,S2							Date		23/04/2025
HAZOP Team Member:	L.R. Hall, P2, P3, P4 and P5	Phase	[P3] Post-Mission					Meeting Date		22/05/2025
Node Discussed:	[N1] Docking									
Design intent:	After arriving at the end of the post mission taxiing route, the drone starts landing procedure									
No.	Parameter	Guideword	Deviation	Probability (1-3)	Possible Causes	Consequences	Severity (1-3)	Safeguards	Comments on Operation	Actions recommended	Action allocated to
9-1:1	Docking Alignment	No	Drone fails to align with docking pad[2]	3	Positioning error; wind drift	Cannot engage latch; remains afloat; trajectory not completed, no data offloading	2	Redudant dualway docking communication between drone and hub.	Drone can not land. runway requires inspection by Kievit, but only after drone is retrieved above non critical ground, delayed opening	Run through Drone and Hub callibration, Run through Drone hardware functioning	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
9-1:2		Other than	Drone misaligned with docking pad	3	Crosswind gust; calibration drift	Drone can land but not optimal, Drone out of use for subsequent trajectories	1	proximity sensors, landing aid equiptment.	Subsequent runway inspections require Kievit, less efficient by not delay.	Run through Drone and Hub callibration, Run through Drone hardware functioning	FMA is responsible for the runway not opening on time, will contact SO responsible for the drone performance
9-2:1	Power Transfer	None	Drone charging does not commence	3	Drone or dronehub internal system failure	Drone out of use for subsequent trajectories	1	power charger checkups regularly	Subsequent runway inspections require Kievit, less efficient by not delay.	Drone hub requires maintenenance.	FMA is responsible for the runway not opening on time, will contact SO, who will contact infrastrucure for the malfunctioning drone hub.
9-2:2		Less	Drone charging commences but less than intended	3	Drone or dronehub internal system failure	Drone out of use for subsequent trajectories	1	pre-dock power testing	Subsequent runway inspections require Kievit, less efficient by not delay.	Drone hub requires maintenenance.	FMA is responsible for the runway not opening on time, will contact SO, who will contact infrastrucure for the malfunctioning drone hub.
9-3:1	Data Offloading	No	Drone does not transfer data to external severs	3	Drone or dronehub internal system failure, external server system failure	Loss of critical inspection data; need to redo runway inspection	2	local redundant storage	Runway requires inspection by Kievit, but only after drone has completed its trajectory, resulting in delayed opening.	Run through Drone and Hub internal systems.	FMA is responsible for the runway not opening on time, will contact SO, who will contact infrastrucure for the malfunctioning drone hub.
9-3:2		Less	Drone partially transfers data (gaps in dataset)	3	Drone or dronehub internal system failure	Incomplete runway report; manual data stitching required; potential safety oversight	1	Gap-detection algorithms, in flight internal backup storage.	Could effect quantity of data, requires extra RYWCC formulation steps but doesn't require inspection by Kievit.	Run through Drone and Hub internal systems.	FMA is responsible for the runway not opening on time, will contact SO, who will contact infrastrucure for the malfunctioning drone hub.
9-4:1	Shutdown Sequence	Not	Drone propellors do not disarm after touchdown	2	Ground-contact sensor failure	Possible damage, difficult retrieval	1	Auto-disarm on contact; motor-kill override	Requires maintenance	Drone requires maintenance,	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance
9-4:2		Other than	Drone propellors disarm before touchdown	2	False-positive contact	Crash landing, o non critical infrastructure	2	Touchdown-only latch with delay	Crash situation needs to be assessed before flights proceed, slight delay,	Drone requires maintenance,	FMA is responsible for the runway not opening on time, who will contact SO responsible for the drone performance

Figure J.9: N9 Worksheet: Pre-Flight Docking

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Colophon

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