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ATYPICAL APPROACHES

Influence of Wind Conditions and ATC Vectoring on the Occurrence of Atypical Approaches

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Correlating the Influence of Wind and ATC vectoring on the Occurrence of Atypical Approaches for runways at Amsterdam Schiphol Airport

Thesis

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Abstract

The approach phase is one of the most safety-critical segments of flight, as aircraft must be precisely controlled in terms of energy (Speed and Altitude) before landing. In some cases, an approach may show non-nominal energy-management behaviour, meaning that the aircraft does not follow the expected energy profile during the approach. These approaches are referred to as atypical approaches. Previous research has shown that atypical approaches occur more frequently during missed approach/go-around cases than during completed landings. However, the role of wind conditions and ATC (Air Traffic Control) vectoring-related factors on atypical approaches at Amsterdam Airport Schiphol remains unclear.

This thesis investigated whether wind conditions and ATC vectoring-related factors are associated with the occurrence of atypical approaches at Schiphol, with particular focus on atypical missed approach/go-around cases. The analysis focused primarily on runways 18C and 18R, with runways 36R and 06 included as secondary runway groups. Atypical approaches were identified within the 6.2 NM to 3.0 NM segment before the runway threshold using an energy-based classification method with a predefined energy-loss threshold of 20 kt/NM. This was conducted using flights trajectory data to calculate the energy-loss rate. Wind components were calculated and summarised within the same gate, including mean wind components, wind variability, maximum tailwind, and tailwind exposure. ATC command data were analysed by given commands in different approach phases and calculating the distance at which aircraft became established on the runway course before the FAF/FAP (Final Approach Fix/ Final Approach Point). Lastly a logistic regression model was used as a supporting analysis to assess whether wind and ATC vectoring features improved atypical approach identification to measure association.

The results for the atypical quantification showed that atypical approaches occurred in 2.8% of the 173454 analysed approaches and were more represented among missed approach/go-around cases than among landed approaches which is consistent with previous research by van Renssen, (2025). Atypical occurrence was also assessed across runway groups, where runway 18C and runway 36R showed the highest atypical approach rates, at 4.25% and 4.82% for the total landings.

Wind results showed that atypical group that resulted in missed approach/ go-around experienced higher wind variability and greater tailwind exposure, with 28.7% of the 6.2 NM to 3.0 NM gate flown under tailwind conditions. However, the wind did not fully explain the occurrence of atypical missed approach/go-around outcomes.

The ATC vectoring results showed that the given ATC commands did not provide strong evidence of a direct relationship between recorded ATC instructions and atypical approach occurrence. A clearer pattern was found in the FAF/FAP establishment analysis. Atypical missed approach/go-around flights were established later than the other groups, at an average distance of 1.60 NM before the FAF/FAP, and 25% were established after the FAF/FAP. This suggests that late runway-course establishment reduced the distance available for energy reduction before final approach.

Lastly, the predictive model showed some improvement when wind and FAF/FAP establishment features were included, indicating that these factors are associated with atypical approach occurrence. However, the model still had limited prediction ability, suggesting that wind conditions and ATC-related factors do not fully explain atypical approaches. Other operational factors are therefore also likely to play a role.

Generative AI Disclosure

For the construction of this thesis, Artificial Intelligence was used as support for the following:

- Improve clarity, grammar and academic flow for writing.
- decoding issues regarding to python code and SQL queries.
- Identifying relevant academic sources for theoretical framework.

The AI source that has been used:

- ChatGPT 5.2

Table of Contents

List of Abbreviations

Abbreviation	*Definition*
ATC	Air Traffic Control
EHAM	Amsterdam Schiphol Airport
EAIP	Electronic Aeronautical Information Publication
FAF	Final Approach Fix
GIFA	Glide Slope Intercepted From Above
IAF	Initial Approach Fix
ILS	Instrument Landing System
Kts	Knots
NM	Nautical Mile
NCA	Non-Compliant Approach
NSA	Non-Stabilized Approach
SIAP	Standard instrument approach procedures
IAP	Instrument approach procedure
LNAV	Lateral navigation
VNAV	Vertical navigation
STAR	Standard Terminal Arrival Route
TMA	Terminal Manoeuvring Area
VEMMIS	Veiligheid Efficiëntie Milieu Management informatie System

List of Figures

List of Tables

1. Introduction

The aviation industry continues to evolve as a result of technological advancements, operational improvements, and increasing air traffic demand. Still, on top of these developments, safety remains the highest priority within flight operations.

The approach phase represents one of the most safety-critical segments of flight (Blajev & Curtis, 2017). During this phase, the aircraft transitions from descent to landing and must be precisely controlled in terms of airspeed, altitude, thrust, configuration, and runway alignment. Accident statistics indicate that, despite this phase representing only a limited portion of total flight time, significant proportion of fatal aviation accidents occur during final approach and landing, (Boeing, 2025). This excessive risk highlights the operational sensitivity of the approach environment. A particularly critical stage of this phase is the final approach segment.

The final approach begins at the Final Approach Point (FAP), this point is where the aircraft intercepts the vertical guidance and horizontal guidance of the approach and begins its continuous descent toward the runway. The distance between the FAF and the runway threshold represents the remaining margin available for the aircraft to achieve and maintain stabilized flight conditions before touchdown (FAA, 2018). As the aircraft descends along this final portion of the approach, altitude and distance to the runway rapidly decrease, leaving progressively less opportunity to correct deviations in speed, flight path, or descent behaviour.

Because the opportunity to correct deviations becomes increasingly limited during this stage, maintaining a stabilized approach is essential for safe continuation to landing. A key safety procedure in this context is the go-around. A go-around occurs when the pilot discontinues the landing and initiates a climb to conduct another approach (FAA, 2025). According to IATA, (2016), operators typically require a go-around when stabilized approach criteria are not met.

To better understand and analyse such deviations from stabilized conditions, Jarry et al., (2018) introduced the concept of atypical approaches which are categorized into two types: Non-Stabilized Approaches (NSA) and Non-Compliant Approaches (NCA). A stabilized approach is characterized by maintaining the correct speed, descent profile, aircraft configuration, and lateral and vertical flight path within prescribed operational limits. An approach is considered non-compliant when interception conditions during the intermediate or final approach segments do not conform to operational documentation requirements (Jarry et al., 2018).

Failure to meet stabilized approach criteria has been associated with increased operational risk. Continued unstable approaches have been linked to incidents such as runway excursions, loss of control, and other approach-and-landing accidents (Moriarty & Jarvis, 2014). This highlights the operational importance of identifying and understanding atypical approaches.

Building on the framework established by Jarry et al., (2018), subsequent research has sought to operationalize and quantify atypical approaches in different airport environments. van Renssen, (2025), applied comparable NSA and NCA classification criteria to Amsterdam Schiphol Airport (EHAM), adapting the definitions to reflect local airspace design and operational procedures. In line with the operational importance of the final approach segment described above, the study focused on the portion of the approach between the FAF and the runway threshold, where stabilization should been maintained. The results showed that 20.2 per 1,000 landings were classified as atypical. Furthermore, atypical approaches were observed to occur 2.5 times more frequently during go-arounds than during completed landings, indicating a strong operational association between approach instability and missed approach execution.

As a follow-up study, Duda, (2026) extended this line of research by examining the earlier portion of the approach, analyzing the segment from the beginning of the approach procedure toward the FAF. The objective was to determine whether upstream operational factors, such as differences in inbound routes, contributed to the occurrence of atypical approaches. However, no statistically significant relationships were identified, suggesting that other contextual or environmental factors may influence approach stability.

One category of factors that has not yet been assessed is the influence of meteorological conditions and air traffic control (ATC) vectoring on the occurrence of atypical approaches. Weather variables such as wind speed, wind direction can affect aircraft performance, handling characteristics, and pilot workload during the approach phase. These factors may increase the difficulty of maintaining stabilized approach criteria and, consequently, elevate the likelihood of atypical approaches and potential go-around events.

1.1 Problem Statement

For atypical approaches at EHAM, it remains unclear whether their occurrence is associated with specific wind conditions and/or ATC vectoring practices. Without a clear understanding of these potential associations, the factors contributing to atypical approaches remain insufficiently explained, limiting the ability to anticipate, identify, and mitigate elevated instability risks during approach operations especially for atypical approaches that resulted into an go-around.

1.2 Main Objective and Sub-Objectives

The main objective of this thesis is to investigate the relationship between wind conditions, ATC vectoring, and the occurrence of atypical approaches at EHAM by analysing wind parameters, ATC instructions, and flight trajectory data. This thesis aims to determine whether these factors are associated with atypical approach behaviour and to identify potential contributing factors that may support improved detection and mitigation of atypical approaches especially the ones that resulted into an go-around.

Based on the main objective the following sub-objective are necessary:

i. Quantify atypical approaches using the predefined aircraft energy analysis for the final approach segment. This provides the basis for comparing nominal and atypical approaches in the following wind and ATC analysis.

ii. Assess whether specific wind conditions are associated with atypical approach occurrence, and whether these associations vary across operational conditions, runway configurations and landing outcomes.

iii. Analyse the influence of ATC vectoring on the occurrence of atypical approaches. To determine whether ATC instructions are linked to atypical approach occurrence, and whether ATC command patterns help explain why some approaches become atypical.

iv. Evaluate the individual and combined role of wind conditions and ATC vectoring on the occurrence of atypical approach using a predictive model. This aims to assess whether atypical approaches are associated mainly with wind conditions, ATC-related factors, or a combination of both.

1.3 Main question and Sub-Questions

The main research question for this thesis is:

With the current identification criteria for atypical approaches, do wind condition and ATC vectoring has an influence on the occurrence of atypical approach, especially the ones that resulted in to a go-around at Schiphol airport?

For this main question the following sub-question are defined:

i. How can atypical and nominal approaches be classified using the predefined aircraft energy analysis for the final approach segment?
ii. To what extent are specific wind conditions associated with atypical approach occurrence, and how do these associations vary across operational conditions such as runway configurations and landing outcomes?
iii. Are ATC vectoring and command characteristics associated with the occurrence of atypical approaches, and can ATC command patterns help explain why some approaches become atypical?
iv. What is the individual and combined association of wind conditions and ATC vectoring characteristics with the occurrence of atypical approaches by using a predictive model?

1.4 Scope and Limits

This thesis focuses on assessing the influence of wind conditions and ATC vectoring on the occurrence of atypical approaches at EHAM in 2025. The main analysis focuses on runways 18C and 18R during day and night air traffic operations. In this thesis, influence refers to whether wind and ATC characteristics are statistically and operationally associated with atypical approach occurrence, rather than proving direct causality. Runways 06 and 36R are included as a secondary analysis, as for these runway a six-month period in 2025 is taken for the data analysis. These runways are included to examine whether atypical occurrence and wind-related patterns differ across runway configurations. For the identification of Atypical and nominal approaches a predefined energy-based classification criterion is used, which provides the basis for the wind and ATC analysis. It’s important to note that this thesis does not aim to optimise or adjust the classification criterion itself.

1.5 Thesis Structure

This thesis consist of the following chapters. Chapter 2 provides the theoretical framework by introducing the concept of aircraft approaches, different approach types, stabilization criteria, weather conditions, and ATC vectoring. This chapter also reviews relevant literature to provide insight into existing research on the influence of meteorological conditions and ATC vectoring on atypical approach occurrence. Chapter 3 describes the methodology used to conduct the research. As this research follows an quantitative approach the methods includes data collection process, the energy-based classification used to distinguish between nominal and atypical approaches, the calculation of wind components, and the technique used to analyse ATC instructionsChapter 4 presents and discusses the results of the analysis performed to compare wind conditions and ATC instructions between atypical and nominal approaches. Finally, Chapter 5 presents the conclusion and recommendations for future research.

2. Literature Review

This literature review focus on measurable factors that may contribute to deviations from nominal approach behaviour. Section 2.1 and Section 2.2 introduce aircraft approaches and the structure of instrument approach procedures, followed by the stabilized approach concept in Section 2.3. The influence of operational and environmental factors is then examined in Section 2.4 (ATC vectoring) and Section 2.5 (wind conditions), a review of previous studies on these factors is also provided. Finally, Section 2.6 discusses research on atypical approaches and their detection methods.

2.1 Aircraft Approaches

An aircraft approach is the final phase of a flight where an aircraft transitions from cruise or descent altitude toward landing at an airport. Operationally, the approach begins when the aircraft is cleared to execute an arrival or instrument approach procedure and continues until the aircraft lands or a missed approach is initiated (ICAO, 2018).

Approaches occur within the terminal manoeuvring area (TMA), the controlled airspace surrounding an airport where arriving and departing aircraft are instructed and guided by air traffic control. Within this environment, aircraft transition from the en-route phase into the airport traffic system and begin preparing for landing (FAA, 2017; ICAO, 2018).

At EHAM, inbound traffic is organized through structured arrival routing known as STAR (Standard Terminal Arrival Route) that guides aircraft from different sectors into the TMA via IAF's (Initial Approach Fix) as shown in Figure 1. Key routing points within this arrival structure at EHAM include ARTIP, SUGOL, and RIVER, which act as entry points for aircraft entering the Schiphol TMA and distributing inbound traffic flows toward the airport (Kemper & Jerry, 2023). Aircraft approaching through these routing points are vectored by ATC and guided toward the final approach path during day operation.

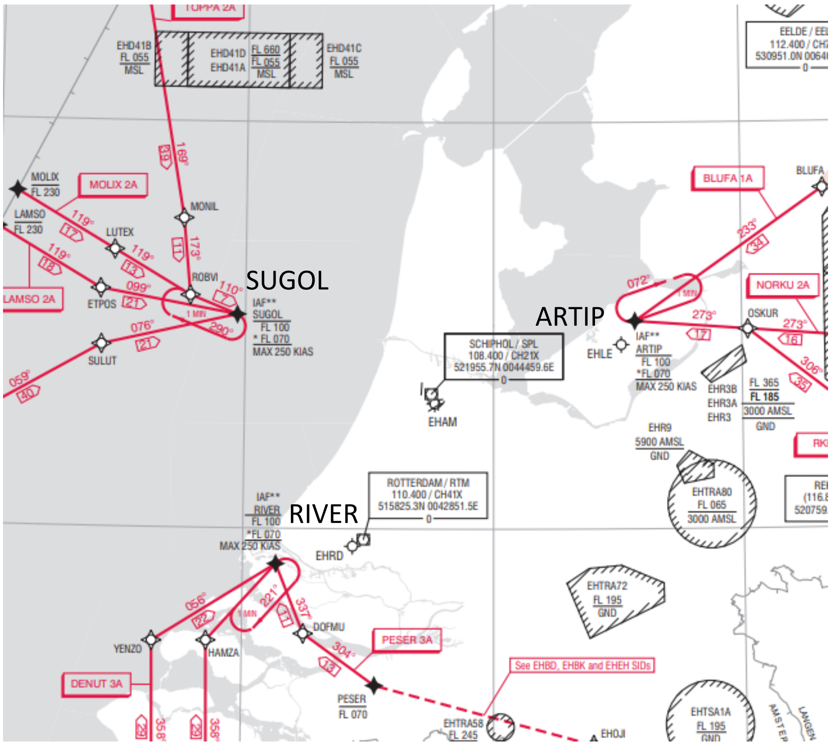

Figure 1: Schiphol STAR's | Source: www.eaip.lvnl.nl

Once an aircraft enter the final approach phase, it must progressively descend toward the runway while configuring the aircraft for landing. From an operational perspective, this descent can be understood as a process of controlled energy management. An aircraft descending carries both potential energy (altitude) and kinetic energy (airspeed). During the final approach, this energy must be reduced in a certain so that the aircraft reaches the runway threshold at the correct speed, descent rate, and landing configuration (FAA, 2017; ICAO, 2018). If this energy reduction does not follow the intended descent profile, the aircraft may arrive too high, too fast, or misaligned with the runway, potentially compromising approach stability (Jarry et al., 2018).

2.2 Structure of Instrument Approach Procedures

Aircraft approaches are conducted under two type of flight rules; Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). Under VFR, pilots navigate primarily using visual references to the ground and surrounding traffic. In contrast, IFR operations rely on navigation instruments and predefined procedures while aircraft are sequenced by air traffic control (ICAO, 2018). At major international airports such as EHAM, the majority of traffic consists of commercial airline operations conducted under IFR, allowing aircraft to operate safely and efficiently in dense traffic environments and during reduced visibility conditions. Because IFR operations rely on predefined navigation procedures, aircraft approaches are typically conducted using instrument approach procedures designed according to ICAO, (2018).

Instrument approaches are divided into clearly defined segments to ensure obstacle clearance and controlled descent toward the runway. As shown in Figure 2 These segments include the initial approach fix (IAF), intermediate approach fix (IF), final approach fix (FAF), and missed approach (MAPt) segments (FAA, 2017; ICAO, 2018). Each segment contains defined altitude constraints, descent gradients, and protected airspace surfaces that ensure safe aircraft separation from terrain and obstacles and are published on the aeronautical information procedures (FAA, 2017). These procedures are developed based on assumptions of normal aircraft performance and predictable navigation behaviour, allowing aircraft to transition safely between approach phases while maintaining the required altitude (ICAO, 2018).

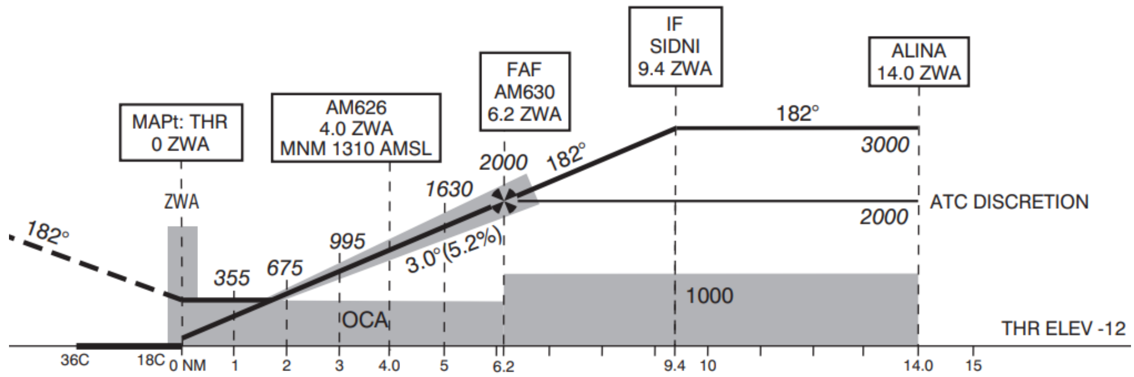

Figure 2: EIAP Instrument Approach Chart EHAM RWY 18C | Source: www.eiap.lvnl

Figure 2 presents the instrument approach chart for Runway 18C at EHAM. In this example, the published approach starts at ALINA, which supports the transition from the arrival environment toward the structured approach path. From there, the aircraft continues toward the intermediate segment (IF), where alignment with the final approach course is prepared and further descent and speed reduction may take place. The approach then continues toward the FAF/FAP, which marks the beginning of the final approach segment (lvnl, n.d.).

2.3 Stabilized Approach

While instrument approach procedures provide structured guidance to support aircraft alignment and descent toward the runway, safe continuation of the approach also depends on the aircraft reaching a stable and controlled condition during the final approach phase. This is where the stabilised approach concept becomes important, as it provides operational criteria for determining whether an aircraft is suitably configured, aligned, and energy-managed before landing. The stabilised approach concept is widely recognised as an important operational barrier against approach-and-landing accidents. According to (FSF, 2000), maintaining a stable aircraft condition during the final approach phase reduces the likelihood of operational errors and runway-related incidents..

IATA, (2016) generally defines a stabilised approach as one in which the aircraft reaches a controlled and predictable flight condition by a specified altitude above the runway. According to IATA guidance, stabilisation should normally be achieved by 1,000 ft above aerodrome elevation in instrument meteorological conditions (IMC) and 500 ft in visual meteorological conditions (VMC). At this point, the aircraft should be on the correct flight path, maintaining the appropriate target airspeed, configured for landing, and descending at a controlled vertical rate.

These criteria reflect the need for alignment between flight path geometry, aircraft configuration, and energy state during the final approach phase. When these elements remain within acceptable limits, the aircraft can continue toward landing under stable conditions. If the aircraft fails to meet or maintain these parameters, operational procedures may require the flight crew to initiate a go-around rather than continue an unstable approach.

Deviations from stabilised conditions can be related to atypical approach behaviour, measurable flight parameters such as airspeed, vertical speed and lateral or vertical path deviation are therefore relevant for identifying deviations from expected approach behaviour.

Understanding the stabilised approach concept therefore provides a reference framework for identifying when approach behaviour deviates from expected operational conditions. The following sections review existing literature on the detection of atypical approaches and on the possible association between wind conditions, ATC instructions, and deviations from expected approach behaviour.

2.4 Unstable Approaches and Detection

Advances in flight data monitoring and trajectory analysis have enabled the identification of unstable also known as atypical approaches. Many studies focus on detecting deviations from expected flight behaviour using measurable flight parameters such as airspeed, vertical speed, glide path deviation, and aircraft energy state.

Jiao et al., (2018), developed a model to detect unstable approaches using quick access recorder (QAR) data from Boeing 737 operations. This study analysed approximately 30,000 approach segments and identified unstable approach events when several operational parameters exceeded predefined thresholds below 1,000 ft. These parameters included airspeed, vertical speed, aircraft configuration, roll angle, localizer and glide slope deviation, and engine thrust. The results indicated that approximately approaches triggered unstable approach events, with airspeed exceedance and localizer deviation among the most common indicators of instability.

Other studies have examined atypical approaches from an energy-management perspective. Jarry et al., (2018), applied functional principal component analysis to flight trajectory data and identified patterns associated with atypical approach behaviour. Their results showed that atypical approaches frequently involve non-nominal energy states, such as excessive speed or GIFA (glide slope intercepted from above. These situations require significant corrections in descent rate or thrust in order to regain the nominal approach path.

More recently, Chiu & Lai, (2023) developed a machine-learning approach for unstable-approach detection using ADS-B trajectory data. Their model used indicators derived from aircraft speed and altitude to represent the aircraft's kinetic and potential energy states during approach. The deep neural network achieved prediction accuracy of approximately 85% for energy-based indicators and 82% for trajectory deviation, demonstrating that energy-related trajectory characteristics can serve as reliable indicators of instability.

However, an important limitation of many trajectory-based studies is their focus on detecting unstable approach patterns rather than identifying the causal factors behind those patterns. Because trajectory-based analyses rely primarily on identifying unstable approaches, operational or environmental influences such as meteorological conditions, air traffic control instructions, or other contextual factors that contribute to instability may not be fully captured.

2.5 The Influence of Wind on Approach Stability

In addition to operational factors, wind conditions introduce dynamic variability during the final approach phase and may influence the ability of aircraft to maintain a stabilised descent. Changes in headwind, tailwind, and crosswind components can affect aircraft performance, flight-path control, energy management, and pilot workload.

Among these wind-related factors, low-level wind shear represents one of the most significant hazards during approach and landing. ICAO (2005), defines wind shear as a sudden change in wind speed or direction over a short distance and notes that its occurrence below approximately 500 meters above ground level is particularly hazardous for aircraft during approach and landing. In this phase of flight aircraft operate close to the ground with limited margins for speed and altitude deviations, making them especially vulnerable to sudden changes in wind conditions.

Wind disturbances influence aircraft performance in several ways. Sudden reductions in headwind can cause rapid decreases in indicated airspeed and lift, while strong gusts may lead to fluctuations in airspeed and thrust requirements. Crosswinds require additional lateral control inputs and may increase pilot workload during final alignment with the runway. As a result, dynamic wind disturbances can complicate the process of maintaining stable speed and descent profiles during the final approach (ICAO, 2005).

Donavalli, (2016), analysed go-around occurrences at Dallas/Fort Worth International Airport using surveillance data and METAR weather observations. The results showed that wind gusts exceeding approximately 25 kts (approx. 29 mph) and the presence of thunderstorms significantly increased the probability of go-around events. However, reduced visibility alone did not show a statistically significant relationship with go-around occurrence in that dataset. Although Donavalli, (2016) did not analyse atypical approaches directly, the study provides relevant background because it examined the relationship between wind conditions and go-around occurrence. This is important in relation to Renssen (2025), who found that atypical approaches were more frequently observed in go-around cases. Taken together, these studies suggest that wind conditions may be relevant for understanding atypical approach occurrence, especially in approaches that result in a go-around.

A limitation of the study conducted by Donavalli, (2016) is that it was based on only 18 days of data at a single airport. This limits the findings and highlights the need for broader analyses using longer observation periods and different operational contexts.

Khattak et al., (2025) investigated the relationship between wind shear and missed approaches at Hong Kong International Airport using machine learning techniques. The study analysed operational flight data together with meteorological observations to identify which variables were most strongly associated with missed approach events. Feature-importance analysis was applied to determine the relative influence of different factors on go-around probability. The results showed that several variables were particularly influential, including the designated approach runway, aircraft classification, the source of wind shear, and the vertical proximity of wind shear to the runway. Wind shear generated by gust fronts significantly increased the likelihood of missed approaches compared to sea-breeze-related wind shear, while wind shear occurring within approximately 400 ft of the runway presented the highest operational risk. The analysis also showed that certain runways (07R and 07C) experienced higher missed approach likelihoods and that narrow-body aircraft were more prone to missed approaches, likely due to reduced stability under turbulent conditions. Based on these findings, the authors recommend improved monitoring of wind-shear conditions and enhanced operational awareness to reduce weather-related approach disruptions.

However, it should be noted that severe wind shear events represent an extreme form of meteorological disturbance and may not occur with the same frequency at all airports. For example, airports such as Hong Kong International Airport are particularly prone to wind shear due to surrounding terrain and coastal meteorological conditions. Nevertheless, the findings highlight the broader influence that atmospheric disturbances, particularly wind-related phenomena, can have on approach stability. Even when extreme wind shear events are less frequent or even not merely present at EHAM, variations in wind conditions may still influence aircraft energy management and increase the likelihood of unstable approaches or missed approach events.

Besides wind conditions, operational factors may also influence approach stability. ATC vectoring and instructions can affect the aircraft's heading, speed, descent profile, and final approach interception. Therefore, the next section review on how ATC-related factors affecting approach behaviour.

2.6 ATC Vectoring and Approach Stability

In high-density terminal areas, aircraft are frequently guided by radar vectoring rather than flying the complete published arrival procedures for EHAM ATC-vectoring is performed especially during day operation (6:00-23:00) (lvnl, n.d.). Radar vectoring allows controllers to manage traffic flows efficiently by issuing heading, speed, and altitude instructions that guide the aircraft toward the final approach path. While this increases operational flexibility, it can also modify the geometry of the approach and the time and distance available for the aircraft to be stabilized.

IATA, (2016) highlighted that stable approaches are more likely when clear communication and optimal sequencing pattern allow aircraft to follow the intended lateral and vertical approach paths in steady flight conditions. Cooperation between flight crews, air navigation service providers, and controllers therefore plays an important role in maintaining approach stability (CANSO, 2013; IATA, 2016).

CANSO, (2013), identified insufficient track miles and speed compression as two important contributors to unstable approaches. Jet aircraft require considerable distance to reduce both altitude and speed during descent. When aircraft are vectored on shorter routes, kept high for extended periods, or instructed by ATC to maintain higher speeds, the remaining distance for controlled energy reduction becomes limited. As a result, flight crews may need to perform steeper descents or rapid configuration changes to regain the intended profile, increasing workload and the risk of instability.

Vectoring instructions can also influence how aircraft intercept the final approach path. Ideally, aircraft first capture the localizer, which provides horizontal guidance that helps the aircraft align with the runway centreline, before intercepting the glide slope, which provides vertical guidance for descent. This allows the aircraft to intercept the descent path from below in a controlled manner. However, if aircraft are vectored too close to the runway or positioned too high, the glide slope may be intercepted from above. In such situations, higher descent rates may be required to regain the correct path, increasing the risk of unstable approach behaviour. Additional operational factors identified in the literature include late descent clearances, large intercept angles, runway changes, and ATC instructions to maintain high speeds for traffic management. Although vectoring improves traffic efficiency, these conditions may reduce the available stabilization window and increase flight crew workload (CANSO, 2013; IATA, 2016).

Research Gap

Overall, previous research has made significant progress in identifying and detecting unstable or atypical approaches through flight-trajectory analysis and operational parameter monitoring. At the same time, many studies examine factors influencing approach instability mostly combined, such as trajectory deviations, procedure design, or weather-related go-around events.

Less research has examined how wind conditions and operational factors such as ATC vectoring interact with aircraft trajectory behaviour during the approach phase.

This thesis therefore focuses on analysing how wind conditions and ATC vectoring characteristics influence the occurrence of atypical approaches, using operational trajectory data to assess whether specific environmental or operational conditions are associated with increased instability during the approach phase.

3. Methodology

This thesis is divided into six main methodological sections, as shown in Figure 3.

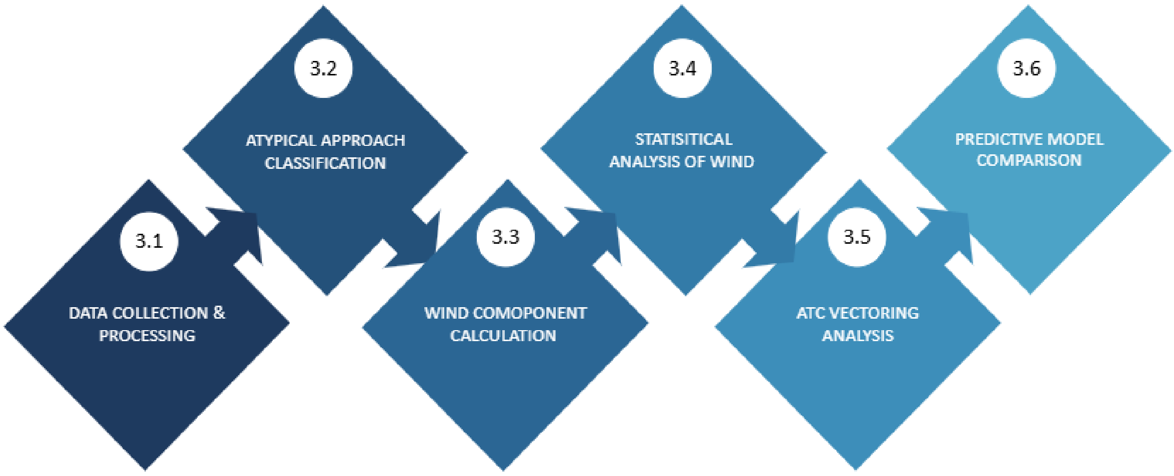

Figure 3: Method structure visualization

In section 3.1, the data collection and preprocessing steps are described. This includes the trajectory data, wind data ATC instruction data. This section also explains how the data were cleaned, prepared, and aligned so that the different data sources could be analysed together.

In section 3.2, the predefined energy-based classification method is briefly explained. This includes the selection of the final approach segment, the calculation of aircraft energy, and the method used to distinguish between nominal and atypical approaches.

In Section 3.3, the calculation of wind components is described. This section explains how wind values were derived from ground speed, true airspeed, track, and heading information, and then transformed into wind components relative to the runway direction. It also explains the approach gates used to extract wind characteristics during the final approach.

In section 3.4, the statistical analysis of wind conditions is explained. This includes the comparison of wind characteristics between nominal and atypical approaches. The purpose of this step is to assess whether atypical approaches has statistically different wind conditions compared to nominal approaches.

In Section 3.5, the ATC instruction analysis is described. This section explains how ATC instructions were matched to flights and approach segments. Trajectory-based indicators, such as approach positioning before or after the FAF, are also included to support the ATC analysis.

Finally, Section 3.6 explains how wind variables and ATC-related operational indicators were assessed together. This step evaluates whether atypical approaches are associated with wind conditions, ATC-related positioning, or a combination of both.

3.1 Data Collection and Preprocessing (VEMMIS)

The data used in this thesis were obtained from the VEMMIS database using SQL queries. The dataset includes Mode C data, Mode S radar data, Enhanced Mode S data, ATC command information from electronic flight progress strips, runway information and operational information related to the analysed approaches.

The main variables used in the analysis are summarised in Table 1. These variables were used to reconstruct approach trajectories, calculate energy and wind-related variables, match ATC commands to flights, group approaches by runway, aircraft type and landing outcome.

Variable	Description	Main use
Flight_id	Unique identifier for each flight	Linking trajectory, ATC, wind, and outcome data
Actual_time	Processed timestamp used for analysis [hh:mm:ss]	Time alignment and day/night classification
Icao_actype	ICAO aircraft type designator	Aircraft type identification
wtc	Wake turbulence category	Aircraft category grouping
Landing_runway	Runway used or assigned for landing	Runway-based grouping
Missed_approach	Indicates whether the approach resulted in a missed approach or go-around	Landing outcome grouping
Lat, Lon	Aircraft position converted in geographic coordinates [DMS]	Distance calculation and approach-position analysis
Alt	Corrected Mode C altitude	Energy calculation and approach profile analysis
Ehs_spd	Ground speed [kts]	Energy calculation and wind calculation
Ehs_TAS	True airspeed [kts]	Wind calculation
Ehs_hdg	Aircraft heading [°]	Wind calculation and approach alignment
Ehs_trk	Aircraft track angle [°]	Wind calculation and trajectory direction
ehs_rocd	Rate of climb or descent [Ft/min]	Energy calculation
Track_id	Radar trajectory identifier	Linking radar records
Command_time	Time at which an ATC command was issued [hh:mm:ss]	Matching ATC commands to flights
command	Recorded ATC instruction	ATC instruction analysis
clc_wspd	Calculated wind speed [kts]	Wind analysis
clc_wdir	Calculated wind direction [°]	Wind component calculation

Table 1: Overview of the main variables used in the methodology

During preprocessing, the different data sources were first linked at flight level and time level. This was required because trajectory data, Enhanced Mode S variables, ATC command information and runway-related information were stored separately. Missing values were not replaced or estimated, as this could influence the results. Instead, flights were only included when the required variables were available for the relevant analysis. The timestamps were converted from UTC to local Amsterdam time to support the day and night operation split. Aircraft positions were converted from local x- and y-coordinates into latitude and longitude using the known radar reference location. Runway threshold coordinates, runway heading, and runway-specific configuration details were obtained from the LVNL eAIP instrument approach charts. Runway reference values were used to calculate the remaining distance and signed distance to the runway threshold. The remaining distance describes the distance from each trajectory point to the threshold along the flight path. The signed distance indicates whether the aircraft was before or after the threshold, with negative values assigned after the threshold was passed. This was needed to identify approach segments and go-arounds occurring after the threshold.

After the required trajectory, runway, time, and distance variables were prepared, the dataset was ready for the energy-based approach classification. The next section explains how the aircraft energy state was calculated and used to distinguish between nominal and atypical approaches.

3.2 Approach Energy Calculation

This section describes how the approach energy state was assessed. It first explains the energy-based classification, followed by the vertical deviation from the nominal glide path as additional context.

3.2.1 Energy-Based Atypical Approach Classification

The initial step before analysing wind conditions and ATC instructions is the classification of the selected approaches as nominal or atypical. In this thesis, the classification is based on a predefined energy-based criterion developed by van Renssen (2025). The criterion is applied to the 2025 approaches to Runways 18C and 18R as primary analysis and the runways 06 and 36R as a secondary analysis.

The criterion evaluates the aircraft's energy state during final approach by combining kinetic and potential energy. Kinetic energy is related to the motion of the aircraft, while potential energy is related to its altitude. For each trajectory point, the total specific energy is calculated using ground speed, vertical speed and corrected altitude, as shown in equation 1.

$$E_t = \frac{1}{2} \cdot ({G_s}^2 \cdot {V_s}^2) + g \cdot h \quad (1)$$

Where E_t is the total specific energy, G_s is the ground speed, V_s is the vertical speed, g is the gravitational acceleration which equals to 9.81 m/s^2 and h is the aircraft altitude. Aircraft mass is not included because mass information is not available in the trajectory data. Therefore, the calculation represents energy per unit mass rather than total aircraft energy.

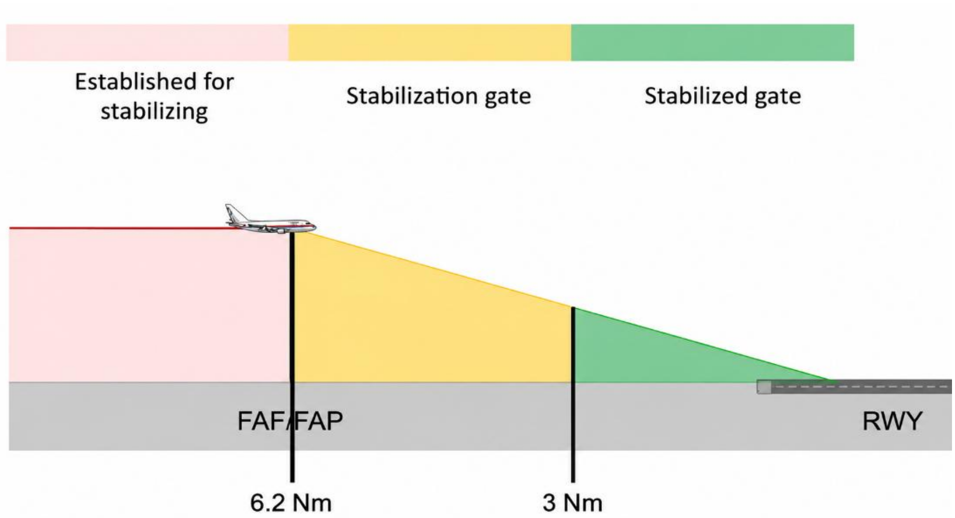

Figure 4: Distance windows used in the energy-based approach classification. |source:www.lvnl.nl

Figure 4 illustrates the distance window used in the energy-based classification. The classification is applied over the segment between the FAF at 6.2 NM and 3.0 NM before the runway threshold. This segment is used as the energy-loss assessment window, where the aircraft is expected to reduce excess energy before reaching the final stabilised part of the approach.

The segment from 3.0 NM to the runway threshold is used to determine the flight-specific reference speed. This reference speed is based on the mean ground speed in this segment and represents the speed condition expected during the stabilised part of the approach. From this value, a nominal energy-loss profile is calculated backwards over the 6.2 NM to 3.0 NM segment using the predefined deceleration criterion.

The observed energy loss of each approach is then compared with its own nominal reference profile. This comparison gives an equivalent deceleration rate in kts/NM. Approaches with an equivalent deceleration rate above 20 kts/NM are classified as atypical, while approaches at or below 20 kts/NM are classified as nominal. This classification is used as the basis for the wind analysis and ATC analysis.

3.2.2 Energy-Based Atypical Approach Classification

In addition to the energy calculation, the vertical position of the aircraft was assessed within the same 6.2 NM to 3.0 NM segment. This was included as a follow-up to the glide path interception from above (GIFA) concept introduced by van Renssen, (2025). Instead of only assessing one interception point, this analysis examined whether the aircraft was above or below a nominal glide path throughout the segment.

For each trajectory point in this segment, the expected glide path altitude was calculated using the distance to the runway threshold and an assumed 3-degree glide path angle. Since the distance was measured in nautical miles and altitude was expressed in feet, the distance was converted to feet before calculating the expected altitude, as shown in Equation 2.

$$h_{glidepath} = h_{treshold} + d_{NM} \cdot 6076 \cdot \tan(3°) \tag{2}$$

Where $h_{glidepath}$ is the expected altitude on the nominal glide path, $h_{treshold}$ is the runway threshold elevation in feet and d_{NM} is the distance to the runway threshold in nautical miles. The constant 6076.12 converts distance in nautical miles to feet and $3°$ represents the glide path angle for a nominal approach. The aircraft's height relative to the glide path was then calculated as:

$$\Delta h = h_{aircraft} - h_{glidepath} \tag{3}$$

Where Δh is the vertical deviation from the nominal glide path and $h_{aircraft}$ is the aircraft altitude. A positive value indicates that the aircraft was above the nominal glide path, while a negative value indicates that the aircraft was below it. This indicator was used to examine whether atypical approaches were associated with being higher than expected during the energy-loss window.

Section 3.3 describes how wind conditions are calculated and transformed into wind components.

3.3 Wind calculation and decomposition

To assess the influence of wind on atypical approaches, the wind information first had to be converted into operationally meaningful wind components. The wind values used in this thesis were calculated from the wind-triangle relationship between the aircraft movement over the ground and the aircraft movement through the air. This ensure information regarding wind condition can be obtained for each trajectory point.

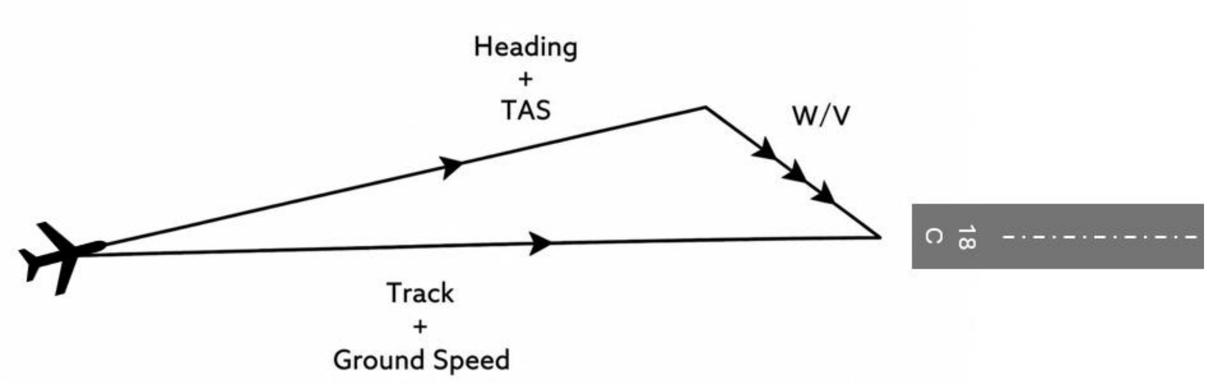

Figure 5: Wind triangle Illustration.

Figure 5 illustrates the wind-triangle relationship used to estimate the wind vector. The aircraft heading and true airspeed define the airspeed vector, which describes the aircraft's movement relative to the surrounding air. The aircraft track angle and ground speed define the ground-speed vector, which describes the aircraft's actual movement over the ground. When wind is present, the direction in which the aircraft is pointing is not always the same as the direction in which it moves over the ground. This difference allows the wind vector to be estimated from the aircraft motion data. The calculated wind vector is defined in equation 4.

$$\vec{W} = \overrightarrow{V_{gs}} - \vec{V_a} \quad (4)$$

Where $\vec{W}$is the calculated wind vector, $\vec{V_g}$is the ground-speed vector, and $\vec{V_a}$is the airspeed vector. The wind-vector components were calculated using vector subtraction. First, the ground-speed vector and airspeed vector were decomposed into x- and y-components. The wind-vector components were then obtained by subtracting the airspeed-vector components from the ground-speed-vector components, as shown in equation 5.

$$\begin{gathered} V_{gs,x} = GS\sin(TT) \mid V_{gs,y} = GS\cos(TT) \\ V_{a,x} = TAS\sin(HDG) \mid V_{a,y} = TAS\cos(HDG) \end{gathered} \quad (5)$$

Where (GS) is ground speed, (TAS) is true airspeed, (TT) is the aircraft track angle and (HDG) is the aircraft heading angle. The wind-vector components were then obtained by subtracting the airspeed-vector components from the ground-speed-vector components, as shown in Equation 6.

$$W_x = V_{g,x} - V_{a,x} \mid W_y = V_{g,y} - V_{a,y} \quad (6)$$

The components W_x and W_y are then used to calculate the magnitude and direction of the wind vector, as shown in equation 7 and 8.

$$clc_{wspd} = \sqrt{W_x^2 + W_y^2}, \quad (7)$$

$$clc_{wdir} = tan^{-1}(W_x, W_y) \quad (8)$$

Where clc_{wspd} represents the magnitude of the calculated wind vector. The wind direction is calculated using $atan2$, because this function uses both wind-vector components and determines the direction over the full 360° range. These two values are then used to decompose the wind into different wind components.

After the calculated wind speed and wind direction were obtained, the wind was decomposed into tailwind/headwind and crosswind components. This was necessary because total wind speed alone does not show how the wind acts relative to the aircraft's direction of movement. The tailwind/headwind component describes the wind effect along the aircraft track, while the crosswind component describes the lateral wind effect perpendicular to the aircraft track. The components were calculated using the aircraft true track as reference, as shown in equation 9 and 10.

$$TWC = -V\cos(TT - W), \tag{9}$$

$$CWC = V\sin(TT - W) \tag{10}$$

Where TWC is the tailwind/headwind component, CWC is the crosswind component, V is the calculated wind speed, TT is the aircraft true track, and $W$is the calculated wind direction.

The components were calculated using the aircraft true track, so the wind was expressed relative to the aircraft's actual direction of movement during the approach. With this convention, positive (TWC) values indicate tailwind conditions, while (HWC) values indicate headwind conditions as a negative tailwind component. For the crosswind component, the absolute value was used. This means that the analysis considered the strength of the crosswind, regardless of whether the wind came from the left or right side of the aircraft.

After the wind components were calculated for each trajectory point, the wind values were aggregated per flight within the 6.2 NM to 3.0 NM distance window before the runway threshold. This window corresponds to the energy-loss assessment window used in the atypical approach classification. For each flight, wind features were calculated for the headwind, tailwind and crosswind components. These included the mean value and variability of each wind component. For the tailwind component, the percentage of the gate flown under tailwind conditions was also calculated. These features were calculated at flight level so that each approach was represented by one set of wind characteristics. The wind features were compared using four operational groups: nominal landed, atypical landed, nominal missed approach/go-around and atypical missed approach/go-around. The resulting flight-level wind features formed the input for the statistical comparison between approach groups, which is described in Section 3.4.

3.4 Statistical Analysis of wind

The statistical wind analysis was used to assess whether the calculated wind features differed between approach groups. The analysis was performed separately for each distance window and runway grouping so that wind conditions before and during the energy-loss window could be evaluated independently.

Descriptive statistics were calculated for each wind feature and group. These included the mean, median, standard deviation, interquartile range and sample size. This provided an overview of the wind conditions in each group before applying statistical tests.

For the comparison of mean wind-feature values between two groups, Welch's t-test was used. Welch's t-test was selected because the analysis compares mean values of continuous wind features between two independent groups. Equal variances and equal group sizes could not be assumed, which makes Welch's t-test more suitable than the standard independent samples t-test. A z-test was not used because the population variances were unknown and the analysis was not based on comparing proportions. Therefore, Welch's t-test was considered the most appropriate test for the two-group wind-feature comparisons. The t-statistic was calculated using the difference between the two group means, divided by the standard error of that difference, as shown in Equation 11.

$$\mathrm{t} = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{{s_1}^2}{n_1} + \frac{{s_2}^2}{n_2}}} \tag{11}$$

where $\bar{x}_1$ and $\bar{x}_2$ are the sample means of the two groups, ${s_1}^2$ and ${s_2}^2$ are the sample variances, and n_1 and n_2 are the sample sizes. After the t-statistic was calculated, the degrees of freedom were adjusted using the Welch-Satterthwaite approximation, as shown in equation 12. These adjusted degrees of freedom were used to calculate the p-value from the t-distribution.

$$\mathrm{df} = \frac{(\frac{{s_1}^2}{n_1} + \frac{{s_2}^2}{n_2})^2}{\frac{(\frac{{s_1}^2}{n_1})^2}{n_1 - 1} + \frac{(\frac{{s_2}^2}{n_2})^2}{n_2 - 1}} \tag{12}$$

For each wind feature, the test was formulated as a two-sided hypothesis test. The null hypothesis assumes that the population mean wind-feature value is equal between the two groups, while the alternative hypothesis assumes that the population means are different:

H₀: *There is no statistically significant difference in the mean wind-feature value between Group 1 and Group 2 (* $\mu_1 = \mu_2$ *).*

Hₐ: *There is a statistically significant difference in the mean wind-feature value between Group 1 and Group 2 (* $\mu_1 \neq \mu_2$ *).*

A two-sided test was used because the analysis assessed whether the mean wind-feature values differed between groups. The p-value was calculated from the t-distribution using the Welch-adjusted degrees of freedom. Therefore, no separate t-critical table was used in the analysis. Results were interpreted using the p-value approach, where differences were considered statistically significant when ($p < 0.05$). Based on this statistical approach, the analysis determines whether observed differences in wind features can be considered statistically significant.

The next section extends the analysis by examining ATC vectoring methods to assess the association with atypical approach occurrence.

3.5 ATC Influence Assessment

In addition to the wind analysis, ATC instruction data were analysed to assess whether recorded controller instructions and final approach path conditions were associated with atypical approaches. The ATC information was obtained from electronic flight progress strips and linked to the trajectory data using the recorded command time. This made it possible to determine where along the approach an instruction was recorded and whether the instruction occurred before or during the energy-loss window.

Table 2 summarizes the most common ATC command codes used in the electronic flight strip data during the approach phase.

ATC Command	Meaning	Brief Explanation
HDG	Heading	Instruction related to aircraft heading.
SPD	Speed	Instruction related to aircraft speed.
EFL	Executive flight level	Instruction related to the assigned flight level or altitude.
DCT	Direct-to	Clearance to proceed direct to a waypoint.
TOC	Transfer of communication	Transfer to another frequency or controller.
REL	Release	Release of control or coordination between sectors.
LBL	Label	Flight label or strip-related system action.
UCO	Under control	Aircraft/control status recorded in the ATC system.
ERA	Erase	Removal or deletion of a system or strip item.
ACK	Acknowledge	System acknowledgement of a command or action.
REV	Revision	Revision of flight or clearance information.
ORQ	On request	Request-related action recorded in the ATC system.

Table 2: ATC command codes used in the electronic flight strip data.

The ATC analysis was mainly focused on commands that may directly influence the aircraft trajectory or energy state, especially heading (HDG), speed (SPD), and executive flight level (EFL). These commands were considered most relevant because heading instructions can affect alignment with the final approach path, speed instructions can affect energy management, and flight-level instructions can affect the descent profile.

For each flight, the number of recorded ATC instructions was determined within predefined approach segments. These segments included before 14 NM, 14.0 NM to 9.4 NM, 9.4 NM to 6.2 NM, and 6.2 NM to 3.0 NM before the runway threshold. This made it possible to compare recorded ATC command activity before and during the energy-analysis gate.

The second indicator used to assess possible ATC influence was whether the aircraft was established on the runway course before reaching the final approach segment. This was based on ICAO Doc 4444, PANS-ATM, Section 6.7.3.2.4(c), which states that when vectoring to intercept the final approach course or track, the final vector shall enable the aircraft to be established on the final approach course or track, in level flight, for at least 2.0 NM before intercepting the glide path or vertical path as shown in Figure 6.

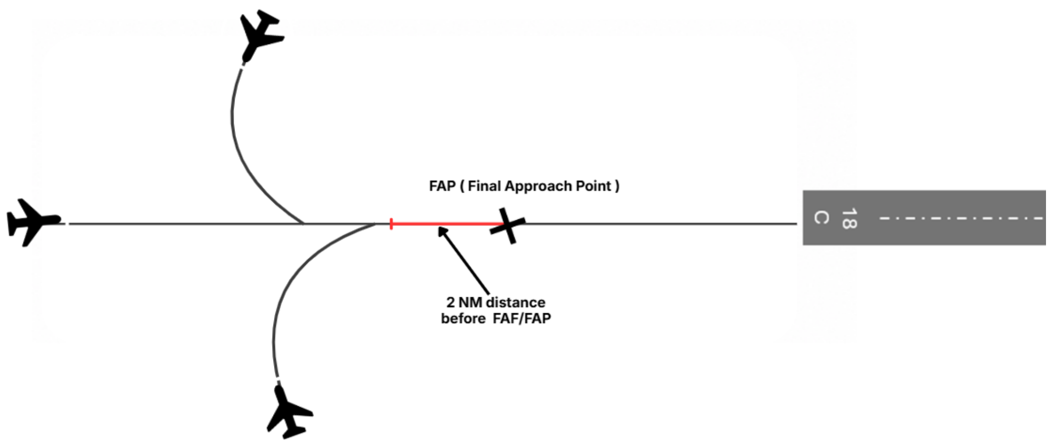

Figure 6: Illustration of the Runway-Course Establishment Assessment

In this study, the criterion was applied by comparing the aircraft true track with the published runway approach direction before the FAF/FAP and calculating the distance over which the aircraft was established. The runway approach directions used for this assessment are shown in Table 2 and were obtained from instrument approach charts in the eAIP. An aircraft was considered established when its true track was aligned with the landing runway direction within a tolerance of ±5°.

Runway	Runway Heading [°]
18R	181°
18C	181°
36R	001°
06	057°

Table 3: Runway Heading Reference for Established Runway Course Compliance

The ±5° tolerance was applied because the analysed data are from 2025, while published runway heading values may vary over time due to changes in magnetic north. Therefore, current eAIP values may not exactly match the runway heading values applicable to the analysed period. The tolerance also accounts for small operational deviations in aircraft track during final approach.

The ATC instruction indicators and final approach path indicators were compared between nominal and atypical approaches and between the four operational groups. This allowed the analysis to examine whether atypical approaches were associated with later establishment, higher altitude relative to the nominal glide path in combination with ATC instruction patterns. The results are interpreted as associations and do not prove that ATC instructions caused the approach to become atypical. And it is important to note that even though all runways were included here it is important that a sensitivity check for each runway will not be included for the analysis of ATC.

3.6 Predictive Model for Support

To assess whether wind-related and ATC-related features added useful information for identifying atypical approach outcomes a predictive model was included as a supporting analysis. The aim was not to prove causality, but to examine whether prediction performance improved when these features were added to a baseline model.

The prediction task was formulated as a binary classification problem. The model estimated the probability that a flight belonged to the target group. Two binary comparisons were used. First, atypical landed flights were compared with nominal landed flights. Second, atypical missed approach/go-around flights were compared with atypical landed flights. In each comparison, the target group was coded as 1 and the comparison group as 0.

Four model configurations were used to assess whether wind and ATC-related features improved prediction beyond operational context. The baseline model included only operation period, stack, aircraft type, wake turbulence category, landing runway, and missed approach status. The other models added wind features, FAF/FAP establishment distance, or both. Variables used directly in the energy calculation, such as altitude, ground speed, vertical speed, total energy, and energy-loss variables, were excluded. Since these variables were already used to define atypical approaches, including them would give the model direct information about the target outcome and could lead to unrealistic prediction performance.

The wind-related features were calculated at flight level within the 6.2 NM to 3.0 NM analysis gate. These included mean headwind, mean tailwind, mean crosswind, headwind variability, tailwind variability, crosswind variability, and tailwind exposure percentage. The ATC-related feature was the distance at which the aircraft became established on the runway course before the FAF/FAP.

The model was implemented in Python using scikit-learn package (a Python-based software library used to build, train, and evaluate machine-learning models) for modelling and performance evaluation. The dataset was split into 80% training data and 20% test data. A stratified split was used so that the proportion of each approach group remained similar in both sets, since some groups contained fewer flights than others.

Logistic regression was selected as the main model because the outcome was binary and the model is easier to interpret. A random forest model was also tested, but it did not provide a clear improvement. Therefore, logistic regression was retained as the main model.

Four model configurations were tested: a baseline-only model, a baseline plus wind model, a baseline plus FAF/FAP establishment model, and a combined model including baseline, wind, and FAF/FAP establishment features. This structure made it possible to assess whether wind conditions, FAF/FAP establishment distance, or their combination improved prediction beyond the baseline.

The Model performance was evaluated using accuracy, precision, recall, F1-score, and ROC-AUC. The results are interpreted as predictive associations rather than effect that explain as a cause. The Improved performance after adding wind or ATC-related features indicates that these factors may contain useful information, however it is important to note that it does not prove that these factors caused the atypical approach outcome more an association.

4. Results and Discussion

In this chapter the results are presented for the atypical approach analysis. Section 4.1 first quantifies how often atypical approaches occurred and how they were distributed across runway groups and landing outcomes. Section 4.2 then examines whether wind conditions show differences between nominal and atypical approaches. Section 4.3 moves to the ATC-related part of the analysis, including recorded instructions, establishment before the FAF and height relative to the nominal glide path. Finally, Section 4.4 presents the machine-learning results, which are used as an additional check to assess whether the selected wind and approach-path variables contain predictive information for atypical missed/go-around approaches.

4.1 Atypical Approach Quantification

Table 4 presents the total number of analysed approaches and the number classified as nominal or atypical using the energy-based classification described in Chapter 3.2 The analysis includes the primary runways 18R and 18C, with runways 36R and 06 included as additional operational context.

Flight Energy type	Number of flights	Percentage [%]
Total Approaches	173454	100
Nominal	168574	97.19
Atypical	4880	2.81

Table 4: Atypical approach quantification.

The results show that 2.81% of the analysed approaches were classified as atypical. This corresponds to approximately 28 atypical approaches per 1,000 analysed approaches. Although this percentage is relatively low, the absolute number remains operationally relevant because of the high traffic volume at EHAM.

To examine the atypical approach occurrence in more detail, the nominal and atypical approaches were further divided into four operational groups based on landing outcome: nominal landed, atypical landed, nominal missed approach/go-around and atypical missed approach/go-around. The results are presented in Table 5.

Analysis group	Number of Flights	Atypical Percentage [%]
Total	173454	-
Nominal landed	168310	-
Atypical landed	4866	2.89
Nominal missed/go-around	264	-
Atypical missed/go-around	14	5.04

Table 5: Atypical approaches per groups.

The results show that 2.9% of landed approaches were classified as atypical, while 5.04% of missed approach/go-around cases were classified as atypical. The percentage of atypical approaches was higher for missed approach/go-around cases than for landed approaches. This is consistent with the findings of van Renssen (2025), who reported that atypical approaches were more often associated with missed approach/go-around outcomes.

To further broaden the quantification of atypical approaches, the atypical rate was also assessed per runway. This was done to examine whether the occurrence of atypical approaches differed between runway configurations. Because the data for runways 36R and 06 only covered the first six months of 2025, the same six-month period was also used for runways 18R and 18C in this comparison. This ensured that the runway-specific results were based on a consistent time period. The runway-specific atypical rates are presented in Table 6.

Runway	Atypical Flights	Total flights	Atypical Percentage [%]
18R	789	39075	2.02
18C	746	17560	4.25
06	1181	30280	3.9
36R	694	14413	4.82

Table 6: Atypical rate per runway.

The results show that runway 36R had the highest atypical rate within the analysed sample, followed by runway 18C. Although runways 18C and 36R had relatively low traffic volumes during the analysed period, they showed the highest atypical rates. This indicates that atypical approaches were not simply concentrated on the runways with the highest number of flights. Instead, the result suggests that runway-specific operational conditions may have influenced the occurrence of atypical approaches. However, this finding should be interpreted with caution. A higher atypical rate on a runway with fewer flights does not necessarily mean that the runway itself is more unsafe. It may reflect the conditions under which that runway was used, such as wind direction, runway configuration, traffic sequencing or approach geometry. Therefore, the results are interpreted as showing where atypical approaches occurred more frequently, not as direct evidence of runway risk.

After comparing the atypical rates between runways, an additional sensitivity check was performed to examine whether atypical approaches were concentrated in specific months or varied across the year. This was included to provide context on whether the observed atypical approach occurrence was consistent over time. Figure 7 presents the monthly atypical rate for runways 18C and 18R over the full year of 2025. These runways were selected for the main seasonal comparison because they were the primary runway groups and had full-year data coverage see appendix D for the .

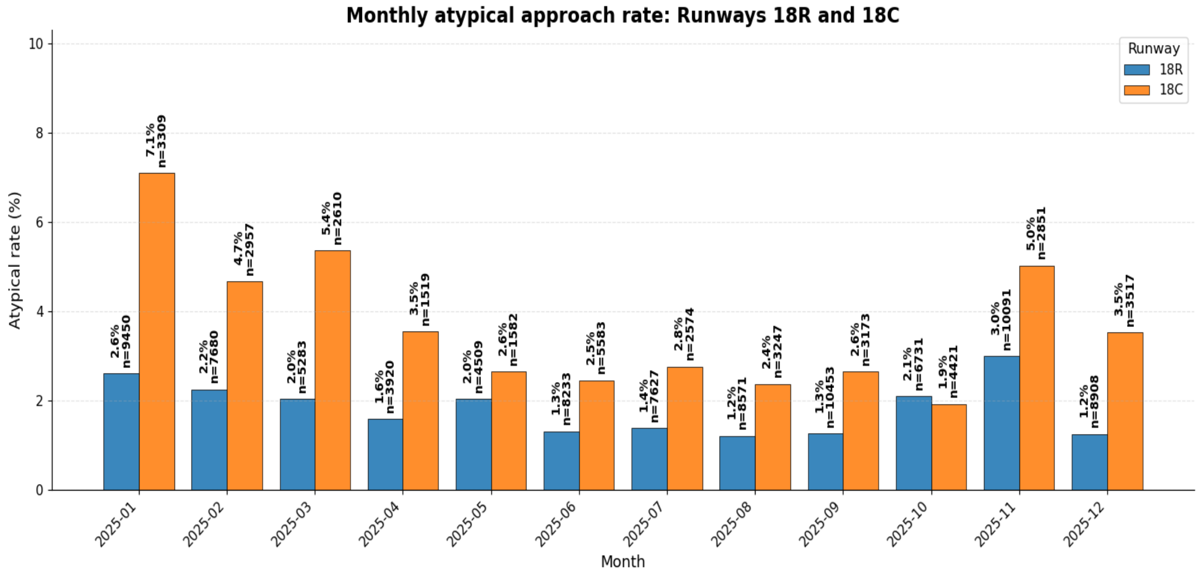

Figure 7: Atypical rate per season

The results in Figure 7 show monthly variation in the atypical rate, but no clear seasonal pattern across both primary runway groups. For runway 18C, the atypical rate was higher at the beginning of the year, especially in January and March, then decreased during the middle of year and increased again toward the end of the year. This pattern was less visible for runway 18C, which showed lower and more stable atypical rates across most months. It shows that atypical approach occurrence varied over time, especially for runway 18C, but it does not by itself explain why these differences occurred.

In addition to the atypical rate, the total specific energy was examined separately for each runway group. This was done to assess whether differences in approach classification were also reflected in the aircraft's energy state see Table 7.

Analysis group	Mean Energy loss [kts/NM]	Percentage from 20 kts/NM [%]
Nominal landed	10.93	- 45.36
Atypical landed	22.47	+ 12.35
Nominal missed/go-around	10.01	- 49.96
Atypical missed/go-around	33.12	+ 65.58

Table 7: Energy loss difference.

Table 7 presents the estimated deceleration values for the four operational groups in relation to the 20 kts/NM atypical threshold. The nominal landed and nominal missed approach/go-around groups both remained clearly below the threshold, with estimated deceleration values of approximately 10 kts/NM. For atypical approaches that landed, the estimated deceleration value was closer to the classification boundary, at approximately 22 kt/NM, which is 12% above the 20 kt/NM threshold. However, The atypical missed approach/go-around group showed a stronger exceedance, with an estimated deceleration value of approximately 33 kt/NM, corresponding to 65% above the threshold. This shows that atypical approaches that resulted into missed approach/go-around had a significantly higher energy-reduction demand within the FAF to 3 NM segment than the other groups. From an energy perspective, this suggests that these flights had a higher excess-energy state, either due to altitude, speed or a combination of both.

Since the mean value for the atypical landed group was close to the 20 kt/NM threshold, the distribution of energy-loss values was also examined, as shown in Figure 8.

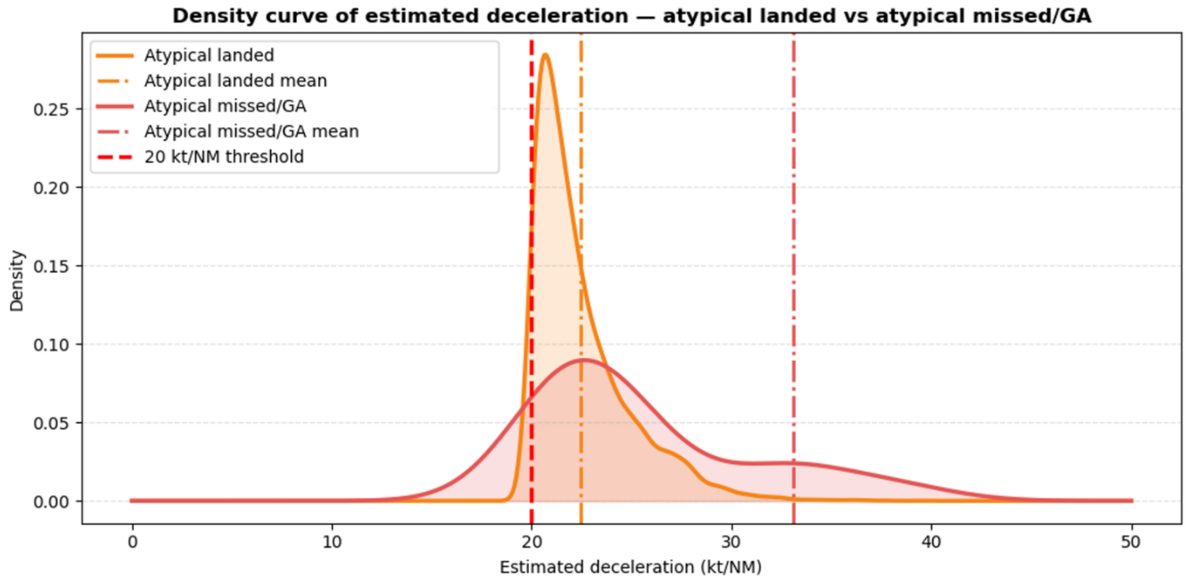

Figure 8: Density curve plot of energy-loss values for atypical groups.

The distribution shows that several atypical landed flights were located close to the classification boundary of 20 Kts/NM showing peak of distribution close to the 20 Kts/NM. This suggests that some flights were only marginally classified as atypical, meaning that a slightly different threshold could have changed the classification of these borderline cases.

Overall, the results in this chapter show that atypical approaches occurred in a relatively small share of the analysed approaches, but were more represented among missed approach/go-around cases and differed between runway groups. The higher estimated deceleration values for atypical missed approach/go-around flights provide additional context for the severity of these approaches. The next section adds further context by examining the vertical deviation from the nominal glide path during the same analysis gate.

4.1.1 Vertical Deviation from the Nominal Glide Path

This section examines the vertical deviation from the nominal glide path during the 6.2 NM to 3.0 NM analysis gate. The indicator was included to provide additional context on whether the aircraft were positioned higher or lower than expected during the same segment used for the energy-based classification that can give an idnciation for the high energy given in the previous section see Table 8.

Analysis group	Flights	Mean Height difference	Mean Glide angle
Atypical landed	4866	67.35	3.13
Atypical missed goaround	14	376.53	3.74
Nominal landed	168310	36.83	3.08
Nominal missed goaround	264	61.68	3.13

Table 8 :Mean height difference relative to the nominal glide path by approach group.

The results shows that the nominal landed group had the lowest mean height difference, at 36.83 ft, followed by the nominal missed approach/go-around group at 61.68 ft and the atypical landed group at 67.35 ft. The atypical missed approach/go-around group had the highest mean height difference, at 376.53 ft. This indicates that atypical missed approach/go-around flights were, on average, much higher above the nominal glide path during the analysed segment. This is also reflected in the mean glide angle, which was highest for the atypical missed approach/go-around group at 3.74°, compared with values close to 3.1° for the other groups. The higher vertical position means that these flights needed to lose more altitude to return to the nominal glide path. This may have increased the energy-management demand during final approach and reduced the margin available for stabilization. Therefore, the vertical deviation results suggest that atypical missed approach/go-around flights were in a less favorable vertical position see Figure 9.

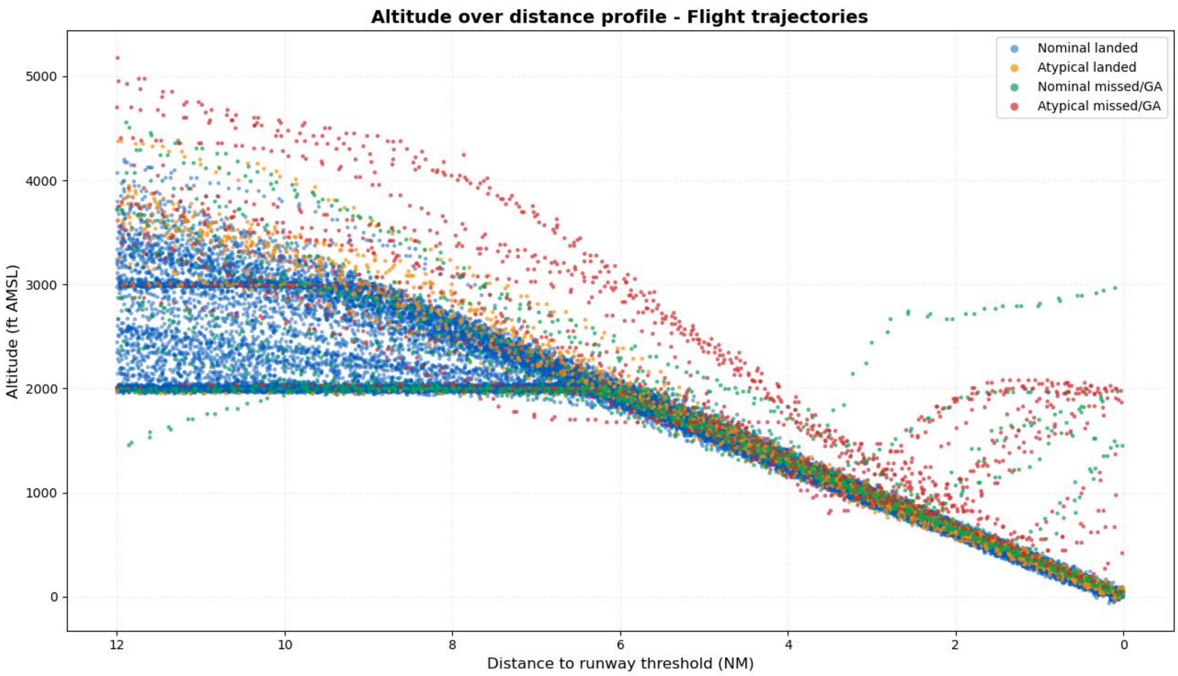

Figure 9: Vertical deviation from the nominal glide path by approach group.

4.2 Wind Condition and Atypical Approaches

This section examines the wind conditions between nominal, atypical landed, and atypical missed approach/go-around flights. The analysis first considers all runways combined, using headwind, tailwind, crosswind, and variability measures.

4.2.1 Mean Wind Components

Figure 10 presents the mean wind-component values for each approach group mentioned above.

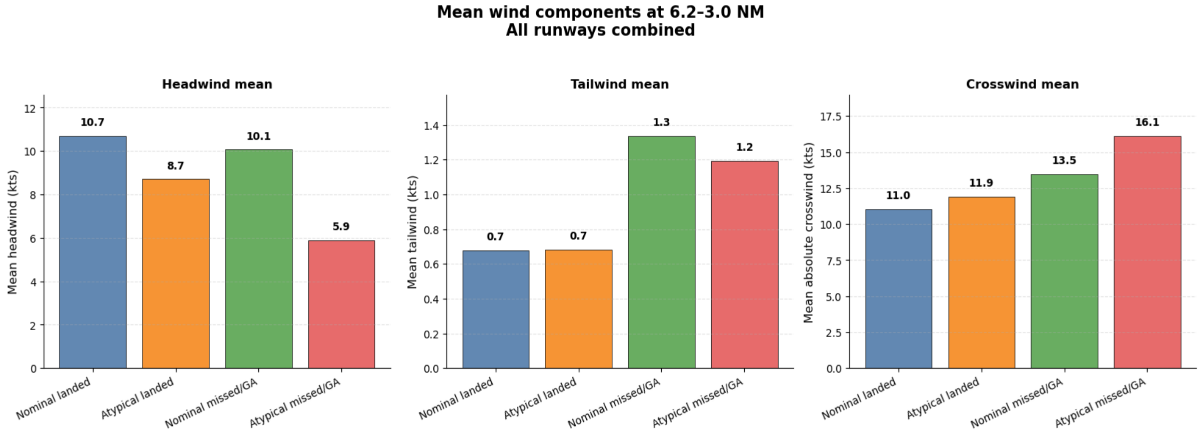

Figure 10: Mean headwind/tailwind and crosswind components group comparison .

The results shows nominal group had the highest mean headwind component at 10.7 kt, while the atypical missed approach/go-around group had the lowest value at 5.9 kt. This indicates that atypical missed approach/go-around flights had less headwind support during the approach. The lower headwind value for the atypical missed approach/go-around group may be less favorable than a higher headwind condition, because higher headwind helps reduce speed and gives the aircraft more time to stabilize during the approach.

For the tailwind component, nominal and atypical landed flights showed similar mean values. The tailwind component was highest for nominal missed approach/go-around flights at 1.3 kts, followed by atypical missed approach/go-around flights at approx. 1.2 kts which shows not a significant difference for tailwind values for these groups. The crosswind component was lowest for nominal landed flights at 11.0 kt and the highest for atypical missed approach/go-around flights at 16.1 kt. This indicates greater lateral wind exposure for atypical missed approach/go-around flights. Crosswind does not directly affect speed reduction in the same way as headwind or tailwind. However, it can be an indirect factor that contributes to limited energy management during the approach as higher crosswind may increase workload during final approach.

Overall, the mean wind-component results suggest that lower headwind support may have made atypical missed approach/go-around flights less favorable for stabilization. However, the tailwind value of 1.2 to 1.3 kts is unlikely to be the main cause of excessive specific energy. The next section examines wind-component variability to assess whether changes within individual approaches provide a clearer explanation.

4.2.2 Wind-Component Variability

Figure 11 presents the average flight-level wind-component variability for each approach group. This metric shows how much the wind component changed during individual approaches, averaged within each group.

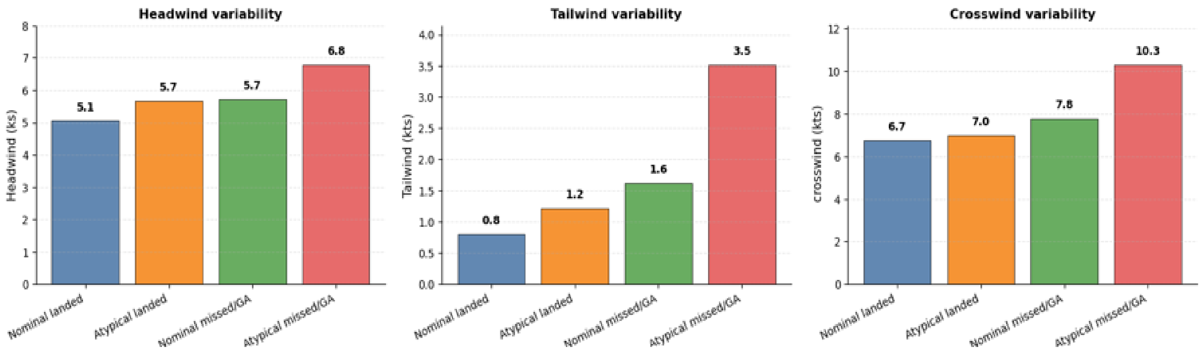

Figure 11. Average flight-level wind-component variability group comparison.

Figure 11 shows that wind-component variability was highest for atypical missed approach/go-around flights across all three components. This group had the highest headwind variability at 6.8 kt, a tailwind variability at 3.5 kt, and crosswind variability at 10.3 kt. Nominal landed flights had the lowest variability across all components. This suggests that atypical missed approach/go-around flights experienced less stable wind conditions during the analysed approach gate. Compared with the mean wind-component results, the variability results show a clearer difference between the approach groups. This indicates that changes in wind conditions during the approach may be more relevant than the average wind values alone, especially for flights that became atypical and resulted in a missed approach/go-around.

4.2.3 Maximum Tailwind and Tailwind Exposure

In addition to wind variability, the maximum tailwind value and the percentage of the gate flown under tailwind conditions were included. The maximum tailwind value was used as a descriptive check, while the tailwind percentage was also used in the statistical analysis see Figure 12.

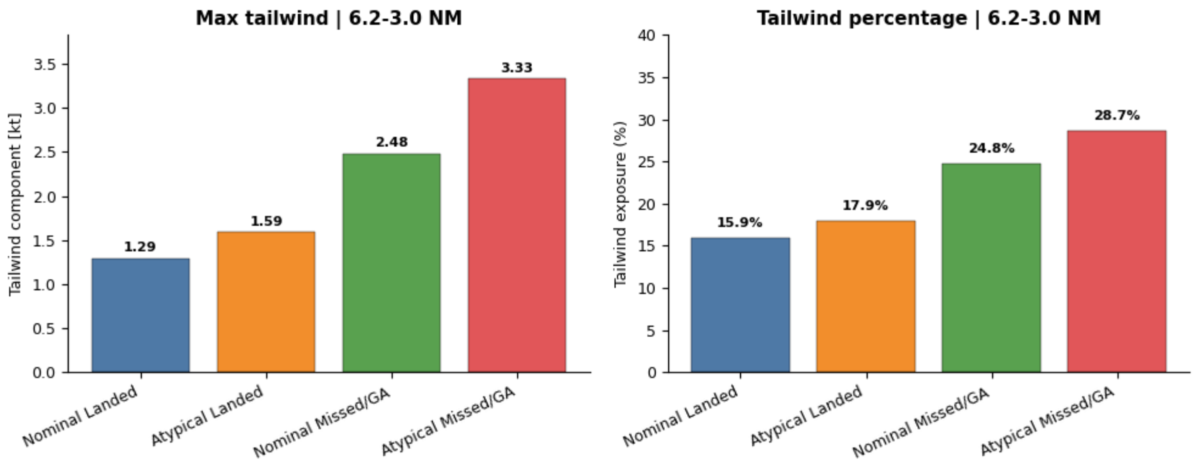

Figure 12:Comparison of maximum tailwind and tailwind exposure by group.

Figure 12 shows that the maximum tailwind values for nominal landed and atypical landed flights were close, with less than 1 kt difference. The atypical missed approach/go-around group had the highest maximum tailwind value, at 3.33 kt, which is consistent with the earlier variability results.

Tailwind exposure was lowest for nominal landed flights at 15.9% and highest for atypical missed approach/go-around flights at 28.7%. This indicates that atypical missed approach/go-around flights spent a larger part of the 6.2 NM to 3.0 NM gate under tailwind conditions. this suggests less headwind support for speed reduction and stabilisation.

4.2.4 Runway -Specific Wind Results

In addition to the overall wind results, a runway-specific sensitivity check was applied to examine whether the wind patterns changed between runway groups. Table 9 summarizes the runway-specific wind patterns identified from the full numerical wind summary presented in Appendix C, The table was used to compare whether the wind conditions observed in the combined all-runway analysis were repeated on individual runways, or whether specific runways showed different wind characteristics between approach groups. The interpretation therefore focuses on whether the runway-level wind patterns appear consistent the combined result.

Runway	Main pattern observed	Interpretation
All	Atypical missed/GA: lowest headwind, highest tailwind exposure, highest crosswind/variability.	Primary combined pattern: atypical missed/GA showed the least favorable wind profile.
18C	Atypical missed/GA: lowest headwind and highest tailwind; nominal missed/GA had the highest crosswind; highest tailwind exposure was also observed.	Partially consistent with the combined pattern; tailwind influence was evident, but crosswind was driven by nominal missed/GA.
18R	Atypical missed/GA: lowest headwind, highest tailwind, highest crosswind, and highest tailwind exposure.	Consistent with the combined pattern; clearest adverse wind profile for atypical missed/GA.
36R	Atypical missed/GA: lowest headwind, lowest tailwind, no clear crosswind difference, and lowest tailwind exposure.	Different from the combined pattern; reduced headwind remained, but tailwind exposure was not elevated.
06	Atypical missed/GA: highest headwind, highest tailwind, highest crosswind/variability, and highest tailwind exposure.	Mixed pattern; several adverse indicators were present, but higher headwind differed from the combined result.

Table 9: Runway-Specific Wind Pattern Comparison

The runway-specific results show that the combined wind pattern was not repeated uniformly across all runways. Runways 18R and 18C showed some consistency with the combined result, while 36R showed a different pattern because atypical missed/GA did not have elevated tailwind exposure.

This is important because 36R had the highest atypical rate, followed by 18C and 06, while 18R had the lowest. Therefore, wind conditions may partly explain runway-level differences in atypical rates, but they do not provide a complete explanation. Other operational factors are likely also involved.

4.2.5 Statistical Comparison Results

This section statistically analyses the observed wind-component values to assess whether differences between approach groups were significant. Two main comparisons were selected because these groups provide the most relevant insight. The first comparison is between nominal landed and atypical landed flights. Table 10 presents the statistical results and interpretation for this comparison.

Statistical Results Nominal landed vs atypical landed				
Wind variable	**Difference**	**p-value**	**Cohen's d**	**Interpretation**
Headwind mean	-1.9795	p<0.0001	-0.2349	Significant difference; Atypical lower; small effect
Tailwind mean	0.0059	0.8382	0.0016	no significant difference; Atypical higher; very small effect
Crosswind mean	0.8726	p<0.0001	0.1074	Significant difference; Atypical higher; small effect
Headwind variability	0.6128	p<0.0001	0.17	Significant difference; Atypical higher; small effect
Tailwind variability	0.4175	p<0.0001	0.1744	Significant difference; Atypical higher; small effect
Crosswind variability	0.252	0.0002	0.0593	Significant difference; Atypical higher; very small effect
Tailwind exposure %	2.1132	p<0.0001	0.0657	Significant difference; Atypical higher; very small effect

Table 10: Statistical comparison of wind-component values between nominal landed and atypical landed flights.

The statistical results show significant differences between nominal landed and atypical landed flights for several wind variables. However, most of these differences had very small Cohen's d values, indicating that the statistical differences were limited in practical size. Therefore, although these variables were statistically significant, the operational relevance appears limited.

The main exception is the headwind component. Atypical landed flights had approximately 2 kt lower headwind than nominal landed flights. This difference was statistically significant and is also more relevant from an operational perspective, as reduced headwind may limit the time available for speed reduction and approach stabilization. In the next section the second comparison group statistical information are given see Table 11.

Statistical Results Atypical landed vs Atypical Missed				
Wind variable	**Difference**	**p-value**	**Cohen's d**	**Interpretation**
Headwind mean	-2.8028	0.1439	-0.3974	No significant difference: Atypical missed lower;
Tailwind mean	0.5104	0.3746	0.2595	No significant difference; Atypical missed higher; small effect
Crosswind mean	4.1837	0.18	0.426	No significant difference; Atypical missed higher; moderate effect
Headwind variability	1.1098	0.3625	0.2663	No significant difference; Atypical missed higher; small effect
Tailwind variability	2.2978	0.1	0.5817	No significant difference Atypical Missed higher moderate effect
Crosswind variability	3.2891	0.0406	0.6485	significant difference; Atypical Missed higher; moderate effect
Tailwind exposure %	10.9246	0.2346	0.3362	No significant difference; Atypical Missed higher; small effect

Table 11: Statistical comparison of wind for nominal landed and atypical landed flights.

The statistical results show no significant differences between atypical landed and atypical missed approach/go-around flights for most wind variables. The only statistically significant difference was found for crosswind variability. Atypical missed approach/go-around flights had 3.2 kt higher crosswind variability, with a Cohen's d of 0.64, indicating a moderate effect size. This suggests that crosswind variability was the clearest wind-related difference between the two atypical groups. The headwind component and tailwind exposure also showed visible differences between the two groups. Atypical missed approach/go-around flights had approximately 2 kt lower headwind and around 10% higher tailwind exposure than atypical landed flights. These differences may be relevant from an operational perspective, as lower headwind support and higher tailwind exposure can reduce the time available for speed reduction and stabilisation.

However, these differences were not statistically significant. This may indicate that the variation within the groups was too large to statistically confirm these differences. Therefore, the results should be interpreted with caution and cannot be used as strong evidence of a difference between the groups.

4.3 ATC Analysis Results

This section presents the results related to ATC factors. It first examines recorded ATC command activity during the approach, followed by aircraft establishment on the runway course before the FAF/FAP. These results are used to assess whether ATC-related conditions differed between the approach groups.

4.3.1 ATC instructions given analysis

Figure 13 provides an overview of all recorded ATC command categories across the distance windows and approach groups. The figure is used to identify the overall distribution of command activity during the approach. The analysis was limited to daytime operations, as ATC vectoring is mainly performed during the day. Nighttime operations were excluded because aircraft generally follow predefined routes during this period, making them less suitable for assessing vectoring-related effects.

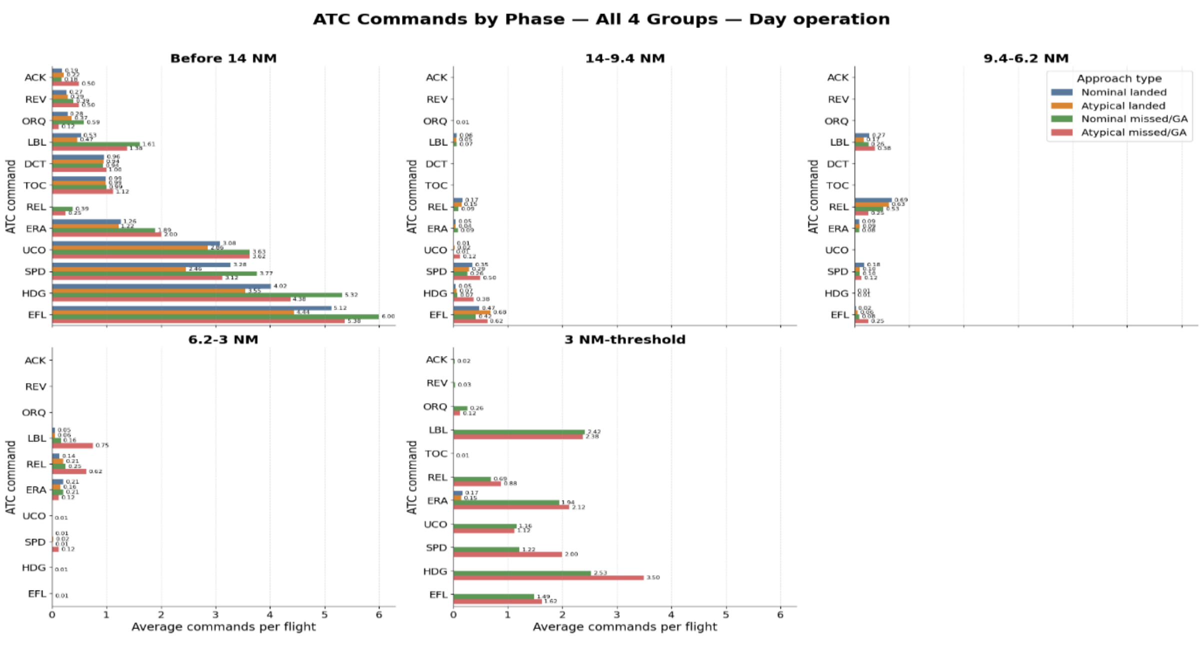

Figure 13: Average recorded ATC commands per flight by command category and distance window.

Figure 13 shows that most recorded ATC commands were given before 14 NM. After 14 NM, the number of commands becomes much lower for most command types and approach groups. Between 6.2 and 3.0 NM, only a small number of commands can be seen. From 3 NM to the threshold, more commands are visible for the missed approach/go-around groups.

This is likely related to the handling of the go-around, rather than showing that these commands caused the approach outcome and it can be seen that only for the approaches that resulted into a go-around had commands in the gate of 3 NM to the runway threshold showing it is a reaction rather the cause for an approach being atypical.

Figure 14 shows that, in the 14 to 9.4 NM window, HDG, EFL, and SPD have the highest recorded command activity for the atypical missed approach/go-around group. This indicates that some flights in this group were still receiving heading, flight level, and speed-related commands in this part of the approach. However, these command types are also visible for the other approach groups, which shows that this activity was not unique to atypical missed approach/go-around flights.

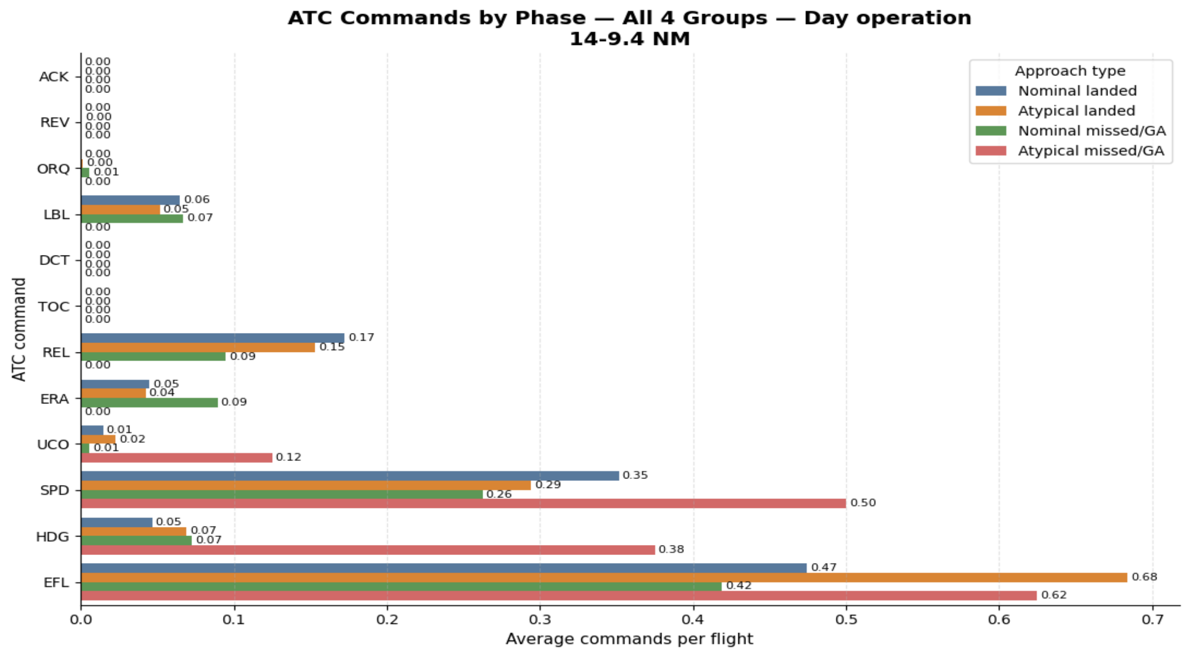

Figure 14: Commands in 14-9.4 NM distance window

This distance window is still closer to the intermediate approach phase rather than the final approach segment. Therefore, vectoring, speed instructions, or flight level commands in this area do not necessarily indicate a negative effect on final approach stability. Although differences between the groups can be seen, the figure does not provide enough evidence to conclude that these commands had a negative effect on the approach outcome. Instead, the figure mainly shows that some approach management was still taking place before aircraft reached the later final approach gates.

For the next phase, the 9.4 to 6.2 NM window, Figure 15 shows that REL is the most frequent recorded command for all approach groups. However, REL is not a direct control command and has limited relevance for explaining aircraft energy management or atypical approach behaviour.

The atypical missed approach/go-around group shows a higher value for EFL, which may indicate that some of these flights still received altitude-related instructions in this phase. For SPD, the nominal landed group shows the highest value, although speed-related commands are visible across all groups.

Overall, the results show some differences between the groups, but they do not provide enough evidence to conclude that recorded ATC commands in this phase explain why flights became atypical.

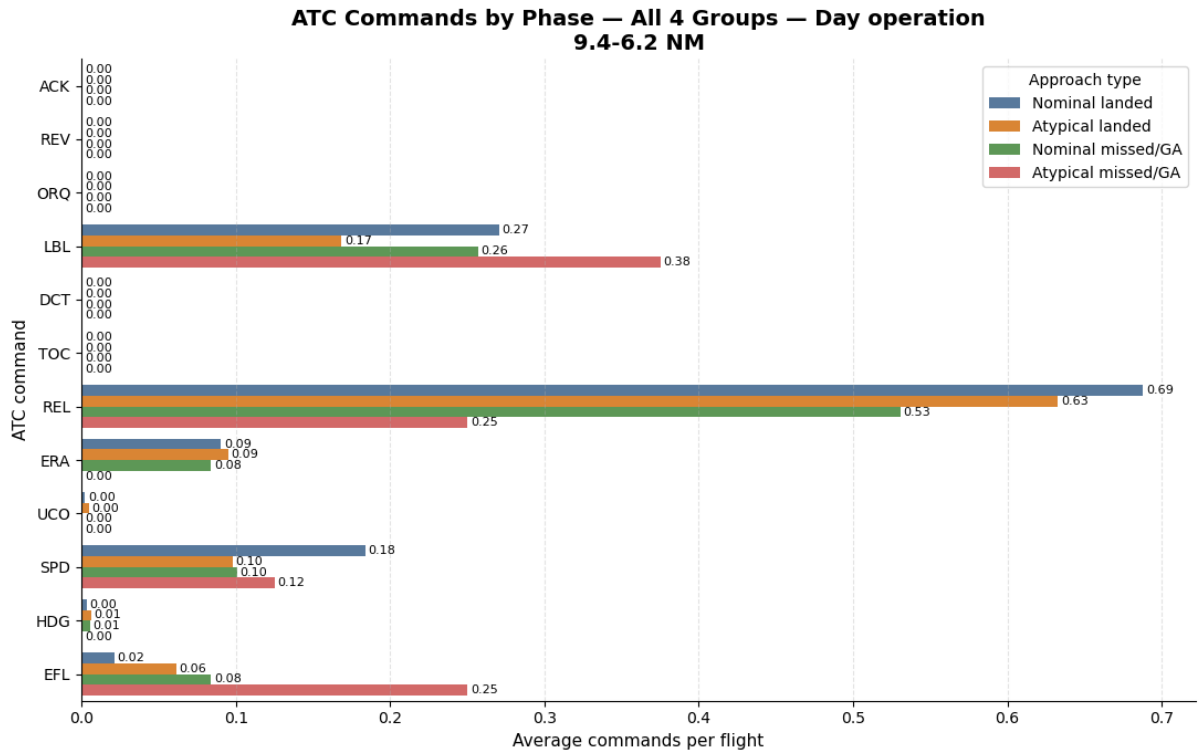

Figure 15: Commands in 9.4-6.2 distance Window

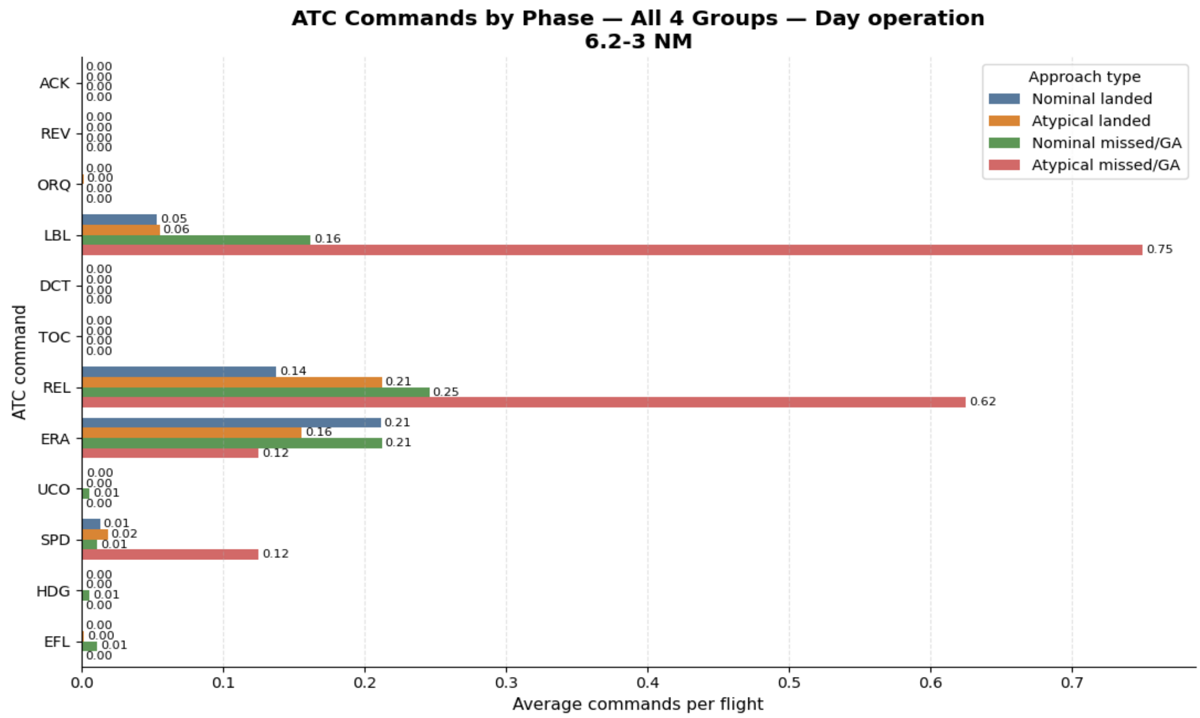

Figure 16: Command in 6.2-3 NM distance window

As shown in Figure 16 the atypical missed approach/go-around group stands out in this window. However, the higher command activity is mainly driven by LBL and REL rather than by direct control instructions such as heading or speed changes. Therefore, the results do not provide strong evidence that ATC commands in this phase were a main factor behind the approach outcome. Instead, the results suggest additional recorded ATC activity for the atypical missed approach/go-around group, but without a clear indication of strong operational influence on approach stability.

Overall, the recorded ATC command results show some additional command activity for the atypical missed approach/go-around group, especially in the later approach windows. However, this increase was mainly driven by system or coordination-related commands, such as LBL and REL, rather than by direct control instructions such as heading, speed, or flight-level changes. Therefore, the results do not provide strong evidence that recorded ATC commands were a main factor behind the atypical missed approach/go-around outcome.

This interpretation should be treated with caution, because the command data were obtained from electronic flight strips. These data may not include all ATC instructions given during the approach, especially instructions given by voice communication. Therefore, the absence of a recorded command does not necessarily mean that no instruction was given operationally. In the following section the second indicator related to ATC vectoring is explained.

4.3.2 ATC Vectoring before FAF results

The second ATC-related factor examined is the distance at which aircraft were established on the runway course before reaching the FAF/FAP, as shown in Figure 17. This indicator is used to assess whether aircraft were aligned with the runway course early enough before entering the final approach segment.

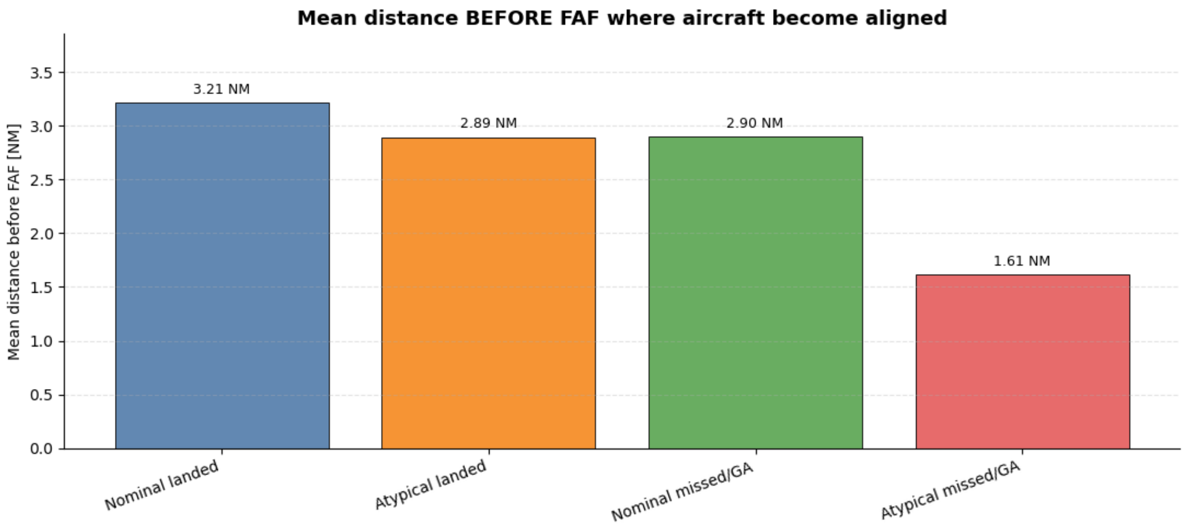

Figure 17: Distance established before FAF/FAP

Figure 17 shows the average distance before the FAF/FAP at which aircraft were established on the runway course for each approach group. The atypical missed approach/go-around group was the only group with an average establishment distance below 2 NM before the FAF/FAP. This indicates that these aircraft were, on average, established later than the other groups.

This result suggests that late establishment on the runway course may be more relevant for atypical missed approach/go-around flights than the recorded ATC command frequency alone. Being established closer to the FAF/FAP leaves less distance available to stabilize the aircraft on the final approach path, which may increase the difficulty of managing specific energy before final approach.

In addition to the average establishment distance before the FAF/FAP, it was also examined whether aircraft became established before or after the FAF/FAP. Figure 18 shows the percentage of flights that were established after passing the FAF/FAP for each approach group.

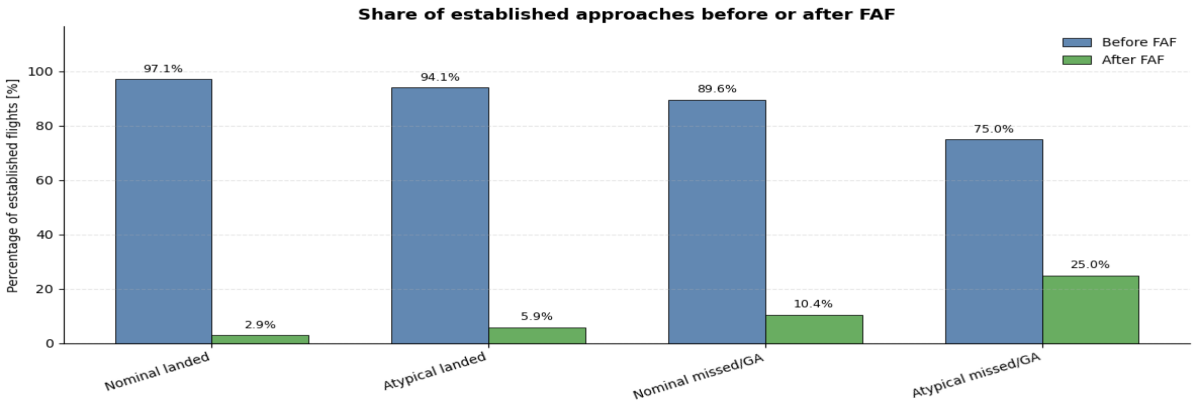

Figure 18: percentage of flights established before and after the FAF/FAP

The Results shows that the atypical missed approach/go-around group had the highest percentage of flights established after the FAF/FAP, at approx. 25%. This supports the previous finding that these flights were established later than the other groups. Establishment after the FAF/FAP means that the aircraft entered the final approach segment without being fully aligned with the runway course, leaving less distance and time to align with the final approach path and reduce excess energy.

This pattern is further illustrated in the trajectory plots for the runways 18R and 18C, Figure 19 shows day operations where vectoring is more visible and several red trajectories, representing atypical missed approach/go-around flights, turn onto the runway course close to the FAF/FAP. Figure 20 shows night operations, where minimal vectoring is visible and most flights followed defined arrival routes toward the final approach path.

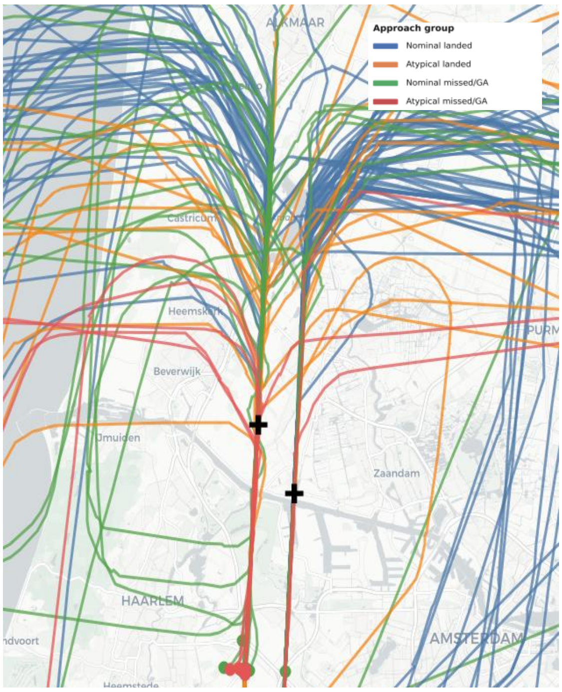

Figure 19: Day-operation flight trajectories around the FAF/FAP.

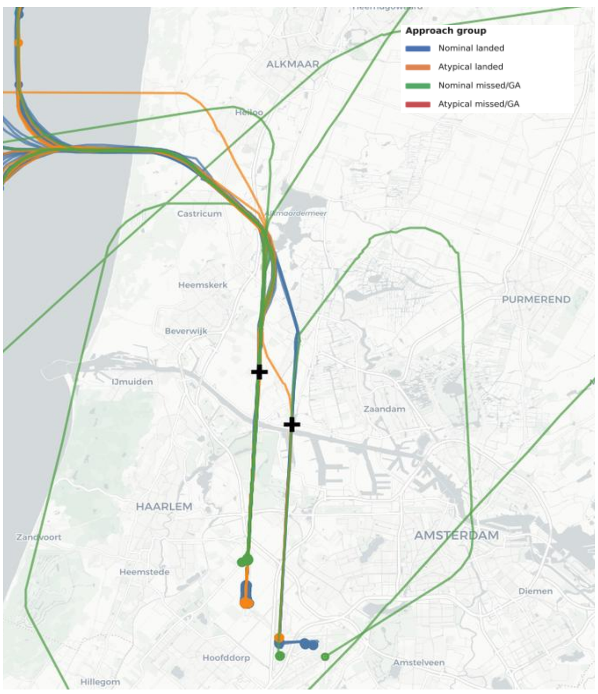

Figure 20:Night-operation trajectories showing defined arrival routes near the FAF/FAP.

Overall, the ATC-related results show that atypical missed approach/go-around flights were established on the runway course later than the other approach groups. This group had the highest percentage of flights established after the FAF/FAP and was the only group with an average establishment distance below 2 NM before the FAF/FAP. This indicates that these flights had less distance and time available to align with the final approach path before entering the final approach segment.

Figure 19 illustrates this interpretation, as several atypical missed approach/go-around flights (red lines in the figure) turned onto the runway course close to the FAF/FAP, especially during day operations where flights were being vectored. This may also help explain some of the wind differences, since aircraft that are still turning may experience different wind components than aircraft already established on the runway course. At the same time, late interception reduced the distance available to align with the runway course and reduce excess energy before final approach.

4.4 Predictive Comparison Model Results

This section presents the results of the predictive modelling analysis. Two main classification tasks were evaluated. The first model distinguishes between nominal and atypical approaches, while the second model distinguishes between atypical landed approaches and atypical missed/go-around approaches. For each model, the baseline feature set was compared with three added-feature sets: wind-only, FAF-only, and the combined wind + FAF feature set. Table 13 presents the main model performance metrics, including balanced accuracy, F1-score, and ROC-AUC.

Predictive Model Results						
Model comparison	**Features Added**	**Bal. Acc. Base → New**	**Δ Bal. Acc.**	**F1-score**	**ROC-AUC**	**Interpretation**
Atypical vs nominal	Wind only	0.634→0.658	0.025	0.092	0.716	Very small improvement
Atypical vs nominal	FAF only	0.634→0.664	0.030	0.088	0.711	Small improvement
Atypical vs nominal	Wind + FAF	0.634→0.676	0.042	0.097	0.735	Small improvement
Atypical landed vs atypical missed/GA	Wind only	0.538→0.559	0.021	0.009	0.524	Very small improvement
Atypical landed vs atypical missed/GA	FAF only	0.538→0.603	0.065	0.010	0.629	Moderate improvement
Atypical landed vs atypical missed/GA	Wind + FAF	0.538→0.621	0.083	0.013	0.600	Moderate improvement
Nominal landed vs atypical landed	Wind only	0.634→0.659	0.025	0.091	0.715	Very small improvement
Nominal landed vs atypical landed	FAF only	0.634→0.664	0.030	0.088	0.711	Small improvement
Nominal landed vs atypical landed	Wind + FAF	0.634→0.676	0.042	0.097	0.734	Small improvement

Table 13: Predictive model performance for the tested feature configurations.

The results show that adding wind and FAF-related features improved model performance compared with the baseline model. For all comparisons, the added-feature models produced higher balanced accuracy (Bal. Acc.) than the baseline, indicating that these variables contributed some additional information for distinguishing between the outcome groups.

However, the improvements were modest. Wind-only features generally produced smaller improvements than FAF-only features, while the combined wind + FAF model produced the largest increase in balanced accuracy. This suggests that FAF-related information may contribute more to the model than wind-only information, and that combining both feature groups provides the best performance among the tested alternatives.

Nevertheless, the overall model performance remains limited. Although balanced accuracy increased, the absolute balanced accuracy values remain moderate (below 0.70) and the F1-scores are very low (<0.1). This indicates that the model is still weak to accurately identify the positive or minority class. The low F1-scores suggest that the model may still produce many false alarms and that the added features are not sufficient on their own to create a reliable classifier.

Therefore, the results should be interpreted as evidence that wind and FAF/FAP establishment features are associated with some improvement in model performance. This suggests that these factors contain useful information for identifying atypical approaches. However, the improvement was not strong enough to indicate an operationally reliable prediction model, which suggest that other factors may influence whether an approach becomes atypical.

5. Conclusion

The main objective of this thesis was to investigate the relationship between wind conditions, ATC vectoring, and the occurrence of atypical approaches at EHAM. This was done by analysing wind parameters, recorded ATC instructions, and flight trajectory data. The aim was to determine whether these factors were associated with atypical approach behaviour and to identify potential contributing factors, especially for atypical approaches that resulted in a missed approach/go-around.

Atypical approach classification

The first sub-objective was to quantify and classify atypical approaches using the predefined aircraft energy analysis for the final approach segment. Atypical approaches were identified within the 6.2 NM to 3.0 NM segment before the runway threshold using the 20 kt/NM energy-loss threshold. The results showed that atypical approaches occurred in 2.8% of the analysed approaches. When comparing the runway groups, runway 18C and runway 36R showed higher atypical approach rates, at approximately 4.25% and 4.82%, respectively. This indicates that atypical approach occurrence was not evenly distributed across runway groups. However, this runway-level comparison was descriptive and should be interpreted with caution, since runway usage and the number of flights differed between runway groups.

Atypical approaches were more represented among missed approach/go-around cases than among landed approaches. This is consistent with previous research by van Renssen (2025), which also found that deviations from nominal approach behaviour are more relevant in unstable or unsuccessful approach outcomes. However it is important to say that the results in the energy shows that atypical that landed were vary close to the threshold which could show that the classification criteria were to strict.

Wind conditions and atypical approaches

The second sub-objective assessed whether wind conditions were associated with atypical approach occurrence. The wind analysis showed some differences between approach groups, but these differences did not fully explain atypical missed approach/go-around outcomes.

Several wind variables were statistically significant between nominal landed and atypical landed flights, although most differences had limited operational meaning. For atypical landed versus atypical missed approach/go-around flights, only crosswind variability was statistically significant different compared to the nominal and atypical that landed. This suggests that wind variability may be more relevant however a crosswind does not have a direct impact on the flight energy rather more on the workload needed from pilots.

Additionally atypical missed approach/go-around flights showed the highest tailwind exposure, with 28.7% of the 6.2 NM to 3.0 NM gate flown under tailwind conditions, which indicates that these flights had less headwind support for speed reduction that could help with stabilisation. The runway-specific sensitivity check further showed that wind patterns differed between runway groups.

ATC vectoring and atypical approaches

The third sub-objective was to analyse the influence of ATC vectoring on atypical approach occurrence. The ATC command-frequency analysis showed additional recorded ATC activity for the atypical missed approach/go-around group. However, this was mainly related to commands, which do not have a direct effect on approach stabilisation, rather than direct heading, speed, or flight-level instructions.

The second indicator for ATC influence was The FAF/FAP establishment which showed a clearer pattern. Atypical missed approach/go-around flights were established later than the other groups, at an average distance of 1.60 NM before the FAF/FAP criterion is 2NM. In addition to that 25% of the atypical flights that resulted into a go around were established after the FAF/FAP. This late establishment may have reduced the distance available for energy reduction. It may also help explain some wind-component differences, since aircraft still turning can experience different wind components than aircraft already established on the runway course.

Combined role of wind and ATC-related factors

The fourth sub-objective was to evaluate the individual and combined role of wind conditions and ATC vectoring using a predictive model. The model results showed that wind and FAF/FAP establishment features were associated with some improvement in model performance. This suggests that these factors contain useful information for identifying atypical approaches especially for the group that resulted into missed approach / go-around.

However, the limited model performance indicates that these features do not fully explain atypical approach occurrence. This suggests that other factors not included in the model are also likely to influence whether an approach becomes atypical.

Answer to the main question

With the current identification criteria for atypical approaches, wind conditions and ATC vectoring-related factors show an association with the occurrence of atypical approaches at Schiphol, especially approaches that resulted in a missed approach/go-around. Wind conditions were associated with atypical approaches mainly through reduced headwind support, wind variability, and tailwind exposure. For ATC-related factors, the clearest pattern was late establishment on the runway course before or after the FAF/FAP.

However, these factors do not fully explain why an approach becomes atypical. The predictive model improved when wind and FAF/FAP establishment features were added, but the prediction remained limited. This suggests that wind and ATC-related factors are relevant, but other operational factors not included in this analysis are also likely to influence atypical approach occurrence.

5.1 Recommendation

Based on the results and limitations of this thesis, the following recommendations can be made:

- It is recommended to review the current atypical approach classification criterion. The results showed that some atypical landed flights were located close to the 20 kt/NM threshold. This suggests that the criterion may be sensitive for borderline cases, and that small changes in the threshold could affect whether some flights are classified as atypical.

- It is recommended to include additional operational factors when identifying the factors influencing atypical approaches. Wind conditions and ATC-related factors showed some association with atypical approach occurrence, but they did not fully explain the outcome. Other factors, such as crew workload, aircraft configuration, pilot response together with these two factors may help explain better why some flights become atypical.

- It is recommended to further improve the predictive model for atypical approach identification. The model results suggested an association between wind, FAF/FAP establishment but the prediction performance was limited. A better prediction model could help identify atypical approaches more reliably and assess which factors contribute most to the classification.

5.2 Future Work

- Future research should reassess the current atypical approach classification criterion. This would help determine whether the 20 kt/NM threshold is too strict for the classification of atypical approaches.

- Future work should investigate a wider set of operational factors and combine them in the analysis to better understand what influences atypical approach.

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Appendix A: Reflection

During the six months of working on this thesis project, I had the opportunity to develop both my technical knowledge and my understanding of operational aviation. The project was challenging from the beginning, because it required combining large-scale data analysis with air traffic control operations, wind conditions, and flight procedure concepts. Although these topics were partly new to me at the start, the research process helped me build a much stronger understanding of how aircraft are managed during the approach phase.

A major part of this learning process was working with large amounts of trajectory data. This improved my skills in data preparation, Python programming, and interpreting operational data. I also learned that aviation data analysis requires more than producing figures or statistics. The results need to be connected back to the operational context, because the same value or pattern can have different meanings depending on runway use, wind conditions, or ATC vectoring.

The project also taught me how important it is to keep the research scope under control. Looking back, I would have stayed closer to the original project plan. During the thesis, I sometimes expanded the analysis because I wanted to understand where the underlying problem came from. Although this helped me learn more about the topic, it also made the project broader and more complex than planned.

I would also like to thank Koos Noordeloos and Alejandro Murrieta Mendoza for their guidance and support throughout this thesis project. Their feedback, availability for discussions, and practical insights helped me improve the direction and quality of the research.

Despite these challenges, the project was a valuable experience. I gained knowledge about air traffic control, flight procedures, approach stability, and data-driven analysis in aviation. The project strengthened my analytical skills and improved my ability to work with large operational datasets. Although I already had some Python experience, this thesis broadened my Python and SQL skills, especially in data cleaning, preprocessing, and analysis. I also developed stronger skills in statistical reasoning, data interpretation, and connecting analytical results to operational aviation context.
Overall, this thesis has been an important learning experience that will be useful for my future work in the aviation field.

Appendix B: AI Disclosure

Generative AI Disclosure Form

1. Introduction

This form is designed to inform about the use of Generative Artificial Intelligence (AI) in this thesis report and to obtain student acknowledgment of responsible usage.

2. Student Information

Name	Student ID
Jaden Mauricia	**500894313**

HvA Supervisor: A. Murrieta Mendoza
Date: 28-06-2026

3. Use of AI-Generated Content

Please indicate how you have used[1] AI-generated content in your report (check all that apply):

- ☒ **Generating ideas or brainstorming**
- ☐ **Drafting text or summaries**
- ☒ **Revising or refining written work**
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- ☐ **Data analysis or interpretation**
- ☒ **Coding or programming**
- ☐ **Converting voice recordings to text**
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- ☐ **Other (please specify): ______________________________**
- ☐ **I have not used generative AI in this report**

Please indicate what AI software was used (also include version number):

ChatGPT 5.2

4. Prompts Used **Please provide the exact prompts[2] or instructions you used when interacting with AI tools and where in the report this information was used - please do NOT include the AI response: Prompts used**	**Where was the information used?**

[1] Describe how the content that has been generated by AI has been used for your own work.
[2] The student may copy-paste the prompt history from the AI-tool(s) used.

How can Improve the clarity, grammar, and academic flow of this paragraph.	Used throughout the report to improve wording in the introduction, methodology, results, conclusion, recommendations. It's Important to note that the detailed information were excluded.
Help me check or improve this SQL query for extracting the required data.	Used during data collection and preprocessing.
How can interpret statistical metric such as, Cohen's d, balanced accuracy. Explain to me what these metrics tell me and how it relate with other metrics	Used in the statistical analysis and predictive model result interpretation.

5. Acknowledgment of Responsibilities

By filling out this form, I acknowledge that:

- **AI-generated content has been reviewed and edited by me to ensure accuracy and originality.**
- **I take full responsibility for the final submission and compliance with academic integrity policies as stated in OER.**
- **I have read <u>the document with rules and advises related to the usage or generative AI.</u>**
- **I have properly cited or disclosed AI assistance.**
- **I understand that misuse of AI-generated content may have academic consequences.**

Appendix C: Wind Conditions For All Runways

in chapter 4.2.4 an interpretation was given for the wind condition for the runways to see how they differ in this appendix is the number of the wind variables given see appendix table 1.

Runway	Approach group	N flights	Mean headwind	Mean tailwind	Mean crosswind	Tailwind exposure %	Headwind variability	Tailwind variability	Crosswind variability
6	Atypical landed	1179	9.6	0.3	8.3	11.2	5.9	0.6	5.9
6	Atypical missed/GA	2	10.8	1.13	19.8	20.7	9.7	0	11.9
6	Nominal landed	29040	9.1	0.6	8.8	11.2	4.8	0.6	5.6
6	Nominal missed/GA	57	9.9	0.8	7.5	14.8	5.4	0.8	5.9
18C	Atypical landed	1328	8.7	0.7	12.9	19.3	5.3	1.1	7.4
18C	Atypical missed/GA	1	0.9	1	12.5	64.3	3.6	3.9	7.8
18C	Nominal landed	35980	11.6	0.5	11.4	15.2	5.1	0.7	7
18C	Nominal missed/GA	27	10.4	0.8	15.4	23	5.6	1.2	7.8
18R	Atypical landed	1677	9.4	0.8	14.3	20.4	5.9	1.5	7.7
18R	Atypical missed/GA	6	6.8	2.3	20.9	43.5	6.8	6.2	10.4
18R	Nominal landed	89616	11.4	0.8	12	17.3	5.1	0.9	7.1
18R	Nominal missed/GA	141	11.7	1.7	16.8	28	6.4	2	8.8
36R	Atypical landed	682	5.6	0.9	10.5	24.7	5.4	1.7	6.4
36R	Atypical missed/GA	5	3.9	0.3	9.6	6.9	6.3	1.7	10.1
36R	Nominal landed	13674	6.8	0.8	8.6	18.1	5.4	0.9	6.3
36R	Nominal missed/GA	39	4.1	1.1	9	29.4	3.8	1.8	6.8

Appendix table 1