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Adverse Weather Low-Probality Forecast Effects on Flight Fuel Planning

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A Capstone Project Submitted to Embry-Riddle Aeronautical University in Partial Fulfillment of the Requirements for the Aviation Management Certificate Program

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This Capstone Project was prepared and approved under the direction of the Group's Capstone Project Chair, Dr. Peter E. O'Reilly
It was submitted to Embry-Riddle Aeronautical University in partial fulfillment of the requirements for the Aviation Management Certificate Program

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Abstract

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Title: Adverse Weather Low- Probability Forecast Effects on Flight Fuel Planning

Institution: Embry-Riddle Aeronautical University

Year: 2021

This project aimed to improve the efficiency of flight planning of regular airlines regarding the addition of extra fuel due to weather forecasts with low probability occurrence regarding rain and thunderstorm events (30 and 40% chances).

Recommendations:

- Expand the scope/sample of analyzed flights to include other significant strategic airports.
- Involve Operations Control Center, Air Operations Engineering, and Safety Department in future studies in order to create an effective policy for extra fuel supply (on planning and flight execution).
- Include in the study other meteorological phenomena and conditions that involve flights extra fuel supply, such as FOG, MIST, HAZE.

- Expand the sample to other forecast groups such as FROM, TEMPO, BECOMING within TAF forecasts.
- Create a field in the flight dispatch documentation, specifically in the navigation paper, to provide crew vital information in probabilistic terms of phenomenon occurrences to justify such additional fuel supply.
- Foster debate around how to improve the existing infrastructure for meteorological forecasts within the Civil Aviation system, involving all Stakeholders.

The research contributed to clarifying that, in general, there is a statistically proven relationship of increased flight time when meteorological forecasts were confirmed.

By understanding this reality, rain and thunderstorm events tend to limit or temporarily suspend landing and take-off operations at a given airfield, impacting operations, significantly increasing the probability of flights diverting to other airports, as previously planned when dispatched. Considering the costs and operational effects related to this procedure, adding extra fuel to increase the waiting time is an alternative to reduce the probability of alternating flights. The problem presented here is precisely that, demonstrating a causal link between the lengthening of the flight time when forecasting low probability rain and thunderstorm events, which would justify the need for extra fuel supply.

The analysis of results was performed based on the Test Student model. This hypothesis test used statistical concepts to reject a null hypothesis when the test statistic follows a normal distribution. The test was performed by comparing two samples, considering flights planned at proposed times when there were weather forecasts with and without confirmation of this event at the scheduled landing times.

During the research, another relevant aspect identified by the researchers was the inexistence of a policy based on scientific studies, at least among the large Brazilian airlines, that considers the effects of flight time extension to determine the amount of extra fuel to be filled. In a given flight, when there is a weather forecast with a low probability of occurrence. In other words, this ends up leading to the arbitrary addition of extra fuel. Also, in most cases, this will translate or reflect in a more considerable amount than would be necessary. As a direct consequence, the aircraft carries more weight and consumes more fuel, thus decreasing the efficiency of the operation and resulting in thousands of dollars more spent per year, which could be saved. By facing this challenge, this study proposes to emphasize/discuss the possibility of efficiency gains through implementing a policy of adding extra fuel due to meteorology, based on scientific analyses.

Resumo

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Este projeto tem como proposito melhorar a eficiência do planejamento de voo das companhias aéreas regulares, no que se refere a adição de combustível extra devido previsões meteorológicas com baixa probabilidade de ocorrência, quanto aos eventos de chuva e trovoada (30 e 40% de probabilidade de ocorrência).

Recomendações:

- Ampliar o escopo/a amostra de voos analisados, de modo a incluir outros importantes Hubs estratégicos;
- Envolver CCO, Engenharia de Operações Aéreas e Safety em estudos futuros de modo a criar uma política eficaz para abastecimento de combustível extra para o planejamento e realização dos voos;

- Incluir no estudo outros fenômenos e condições meteorológicas que envolvem abastecimento de combustível extra nos voos, como por exemplo: FOG, MIST, HAZE.
- Ampliar a amostra para outros grupos de previsões como FROM, TEMPO, BECOMING, dentro das previsões TAFs.
- Criar um campo na documentação de despacho dos voos, especificamente na navegação, de modo a prover uma informação robusta aos tripulantes em termos probabilísticos da quantidade de vezes que o fenômeno de fato ocorreu, para justificar tal abastecimento de combustível adicional.
- Fomentar o debate em torno de como melhorar a infraestrutura existente para prognósticos meteorológicos dentro do sistema de Aviação Civil, envolvendo todos os Stakeholders.

Para se compreender esta realidade, eventos de chuva e trovoada tendem a restringir e interromper de forma temporária as operações de pousos e decolagens em um dado aeródromo, causando impacto nas operações, aumentando significativamente a probabilidade de voos alternarem para outros aeródromos, conforme planejamento prévio quando são despachados. Considerando os custos e efeitos operacionais relacionados a este procedimento, adicionar combustível extra para aumentar o tempo de espera é uma alternativa para reduzir a probabilidade de os voos alternarem. A problemática apresentada aqui é justamente essa, verificar a relação entre a dilatação do tempo de voo quando da previsão de eventos de chuva e trovoada de baixa probabilidade, o que justificaria a necessidade de abastecimento de combustível extra.

A análise dos resultados foi realizada com base no modelo de Test Student, que é um teste de hipótese que usa conceitos estatísticos para rejeitar ou reter a hipótese nula, sempre que da existência de distribuição normal de dados. O teste foi realizado comparando duas amostras, considerando voos que foram planejados em momentos que havia previsões meteorológicas com e sem a confirmação deste evento nos horários de pouso planejados.

A pesquisa contribuiu para esclarecer que, de maneira geral, existe relação estatisticamente comprovada de maior dilatação do tempo de voo quando as previsões meteorológicas se confirmam.

Durante a pesquisa, outro aspecto relevante identificado pelos pesquisadores foi a inexistência de uma política embasada em estudos científicos, ao menos dentre as grandes companhias aéreas brasileiras, que considere os efeitos de dilatação do tempo de voo para determinar a quantidade de combustível extra a ser abastecido em um dado voo, quando há existência de previsão meteorológica de baixa probabilidade de ocorrência. Em outras palavras, isto acaba levando a adição arbitrária de combustível extra, sendo que na grande maioria das vezes, isto venha a se traduzir ou refletir em uma quantidade maior do que, de fato seria necessário. Como consequência direta a aeronave transporta mais peso, e consome mais combustível, diminuindo assim a eficiência da operação e acarretando em milhares de dólares gastos a mais por ano, que poderiam ser poupados. Diante de tal desafio (propósito) ou tais fatos, este estudo se propõe a enfatizar / discutir a possibilidade de ganhos de eficiência, através da implementação de uma política de adição de combustível extra devido a meteorologia, baseada em análises cientificas.

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Chapter I

Introduction

Weather has a significant effect on aircraft operations management (Lee, 2011). In commercial aviation, the first step towards a safe and efficient flight is careful preparations. Concerning fuel planning, the flight dispatchers respect all the rules regarding the minimum fuel required for each trip. The Brazilian airlines should comply with the RBAC, *Regulamento Brasileiro de Aviação Civil*, Brazilian Civil Aviation Regulation, Part 121. Managing fuel accurately and efficiently improves safety through additional attention to planning (Flight Safety Foundation, 2017). In addition, Brazilian airlines should consider other factors that may require extra fuel consumption, such as air traffic and adverse weather conditions.

A flight manager strongly considers the weather condition of the destination airport when loading aviation fuel prior to the aircraft's departure (Lee, 2019). Therefore, the weather forecast is one of the determinants of the fuel amount to be supplied to an aircraft for a given flight. Hence, its accuracy plays a very relevant role in a safe and effective operation.

Currently, the Terminal Aerodrome Forecast (TAF) is widely used around the world by airlines for the purposes of meteorological planning of their operations. It is considered a critical aerodrome-related meteorological product for aviation (Mahringer, 2008). In Brazil, the TAF is made by *Centro Meteorológico de Aeronáutica Classe I* (CMA-1), following the provisions in annex 3 of International Civil Aviation Organization (ICAO), meteorology services for international aviation. It is created every 6 hours, with forecasts for international aerodromes valid for 24 hours and domestic airfields for 12 hours. The TAF code provides a complete description of weather conditions predictions that will occur at an airport during a specific period, including all changes considered significant for air operations. The Meteorological Codes Manual (ICAO, 2011) clarifies that TAF can predict these variations through groups of changes: permanent from (FM) and becoming (BECMG), temporary (TEMPO), or forecasting with a probability (PROB) of 30 or 40% of occurring. This refers to when confidence in the forecast is not sufficient, but the predicted magnitude is considered significant for the operations.

Problem Statement

In the FM, BECMG, and TEMPO TAF's groups, the probability of the phenomena occurring is 50% or greater, indicates a very reliable prediction. However, the 30% probability (PROB 30) and the 40% probability (PROB 40) fields do not have this same level of accuracy. This can lead to the question: Will it be necessary for an airline to add extra fuel when the significant weather forecast at the scheduled landing time is PROB 30 or PROB 40?

The traditional answer to this question could be yes, if the phenomenon occurs, and there is no hold time. The possibility of the flight diverting to an alternative airport would be significant. The result being generating costs and possibly even compromising safety. Due to the high level of competitiveness in the airline industry, tight profit margins, and mainly due to high fuel costs (Vasigh, Fleming & Tacker, 2018), airlines are forced to improve their operational efficiency, and in particular fuel consumption efficiency.

According to the Brazilian Civil Aviation Authority (ANAC, 2020), the cost of fuel represented, on average, 30% of the operating expenses of Brazilian airlines in the period between 2017 and 2019. Figure 1 shows the composition of the operational costs of Brazilian carriers among the years 2017 and 2019.

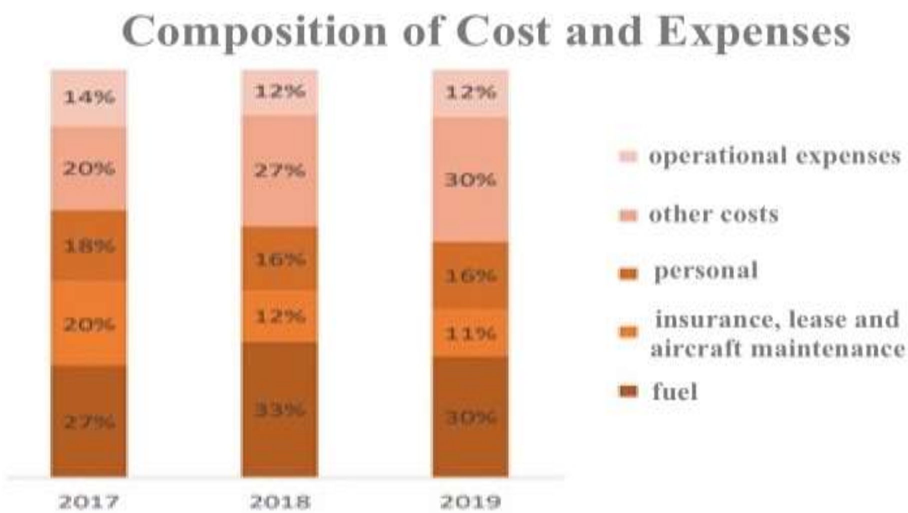

Figure 1 – Brazilian carriers cost composition – (ANAC, 2020)

That said, the purpose of this study is to provide an answer to this dilemma. Based on this theme, the intention of this research is to demonstrate whether it is necessary to add extra fuel in the flight planning. Such steps would be due to meteorology when the significant weather forecast at the landing time is PROB 30 or PROB 40.

Project Definition

This research project focus will be to:

- Assess weather data (forecast and actual observation) to provide a confirmation of occurrence probability.

- Evaluate the existence of the low-probability events correlating with the trip time increment.
- Assess the need for additional fuel supply when low-probability events exist.
- Recommend a flight planning model when low-probability forecast events are observed.

Project Goals, Scope and Contributions

This Capstone Project endeavors to improve flight planning efficiency when the flight's estimated time of arrival coincides with PROB30 and PROB40 forecast in TAF. Through the analysis and crosscheck of weather forecasts with the real-time condition for the year of 2019. Our research attempted, at first, to verify the accuracy of the data and, consequently, the need for extra fuel on flights dispatched in this condition.

Consequently, with the evidence of the data, the project demonstrates that flights could be more cost efficient with better fuel planning. Thus, flights will be dispatched with greater fuel precision and more accurate extra fuel. In addition to that, other benefits from this study will identify fewer pollutants emissions and greater payload availabilities. The research gave special attention to more critical routes that require closer attention from flight dispatchers.

According to a major Brazilian Airline policy regarding fuel flight planning, the extra fuel addition for meteorological purposes is divided into two aspects:

I. For route adverse weather conditions, flights will receive an additional amount of fuel as follow:

Flight Time	***Additional Extra Fuel Value***
Up to 60 minutes	200 kg
From 61 up to 120 minutes	300 kg
Above of 120 minutes	350 kg

Table 1 - Amount of extra fuel due to Sigmet

II. Greater extra fuel amount will be provided when:

i. Destinations have a disruptive scenario or irregular operations (IROPS) due to adverse weather.

ii. Extended flight time is expected due to air traffic control.

iii. Any other occurrence that implies increased consumption.

This research endeavored to improve the flight planning efficiency for a given airline. Also, it can contribute to other airlines. This would lead to cost and quality improvements to the entire Brazilian aviation industry. In the same way, it enhances operational efficiency during flight planning without affecting the safety margins in compliance with RBAC 121 rules.

Research Questions

This research paper will try to answer the following:

- What is the meteorological products' accuracy concerning predicted and observed correlation?

- What is the flight studied percentage affected by flight time increment when predicted meteorological phenomena happen?
- In the affected flights' sample, what is the average increased flight time?
- What is the additional fuel need for flights with low probability forecast events?

Definitions of Terms

ACARS — It is system for exchanging information (messages) between the aircraft and the ground, coded numerically by a radio or satellite link.

BECMG — Abbreviation for becoming. This change indicator describes changes where the conditions are expected to reach or pass specified values at a regular or irregular rate (ICAO, 2011).

CMA — Abbreviation for the meteorological aeronautical center. It is responsible for issuing all meteorological products concerning Brazilian aviation.

ICAO — Abbreviation for the specialized United Nations agency responsible for promoting safety development and regulations for global civil aviation.

IROPS — IROPs, abbreviating the term IRregular OPerations, refer to extraordinary situations in which a flight does not operate as scheduled. There is no clear-cut definition, however, and that umbrella term generally includes delays, cancellations, diversions of flights and similar events (Valput, 2020).

FM Abbreviation for from. It is used to indicate self-contained time periods within the overall validity period during which certain conditions prevail (ICAO,2011).

PROB Abbreviation for probability. Followed by a percentage (rounded to the nearest ten) indicates the probability that a certain change or value will occur (ICAO,2011).

RBAC 121 It is the abbreviation for the regulation that standardizes the laws and procedures related to the Brazilian commercial aviation industry.

SPECI The SPECI acronym roughly translates as Aviation Selected Special Weather Report. SPECI is merely the code name given to METAR formatted products which are issued on a special non-routine basis as dictated by changing meteorological conditions.

TAF Terminal Aerodrome Forecast. It is a message with a defined format with the objective to report a weather forecast for a single airport and its vicinity (ICAO,2011).

TEMPO Abbreviation for temporary. This indicator is used to describe temporary fluctuations in the meteorological conditions, lasting less than one hour in each instance and, in the aggregate, covering less than half of the forecast period (ICAO,2011).

List of Acronyms

ACARS Aircraft Communication Addressing and Reporting System

ANAC Agência Nacional de Aviação Civil

BECMG	Becoming
CMA	Centro Meteorológico de Aeronáutica
FM	From
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IROPS	Irregular Operations
PROB	Probability
TAF	Terminal Aerodrome Forecast
TEMPO	Temporary
RBAC	Regulamento Brasileiro de Aviação Civil

Plan of Study

In Chapter Two, this research reviewed the literature referring to articles and publications related to the topic. The study used samples collected from a national airline database.

In Chapter Three, this paper showed the methodology used. The analysis units came from planned flights, contrasted with their execution. It was correlated with predicted fuel versus average flight time and actual fuel consumed. Also, the project analyzed the need for extra fuel.

In chapter IV, the conclusions obtained through the compilation of data and statistical analysis were presented.

In chapter V, based on the results and conclusions reached, the researchers presented their recommendations and suggestions for future studies.

Chapter II

Review of the Relevant Literature

The aviation industry is a highly competitive environment where operating costs are extremely high. In addition, profit margins are very tight (Vasigh, Fleming & Tacker, 2018). As a result of the growing international pressure to reduce CO_2 emissions in the atmosphere, airlines are being encouraged to improve their operational efficiency. They are looking for new ways to reduce fuel consumption on their flights (ICCT, 2020).

According to ANAC (2020), fuel represented on average 30% of operating costs for Brazilian carriers between 2017 and 2019. Regarding CO_2 emissions, on 7 October 2016, the 39th ICAO Assembly adopted a resolution to establish a global market-based measure in the form of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The purpose was to offset CO_2 emissions from international civil aviation above 2020 levels. Participation was voluntary during the first phase of the program that extends to 2026. However, from 2027 onwards, all ICAO member states will be required to participate in the initiative (ICAO, 2016).

Therefore, it is important to see the urgency of searching for new practices that can help reduce fuel consumption. Initiatives in this regard can bring both economic and environmental benefits to the sector.

Flight Planning and Weather Forecast

The first phase of every commercial flight is flight planning. It is necessary to ensure that all operational and regulatory aspects of a specific flight have been considered. It is also essential for the crew members to carry out their operation safely and effectively (Altus, 2009).

In an airline, the person responsible for developing the flight plan is the flight dispatcher (ANAC, 2020). This professional must observe the current regulations, as well as all aspects related to meteorology, air traffic, and airport infrastructure, amidst others (ICAO, 2015).

Regarding the minimum fuel required to carry out a commercial flight performed by jet aircraft, Brazilian regulations for Airlines (ANAC, 2020) states that the operator must ensure that the aircraft is supplied with mandatory provisions. The guidelines are related to aircraft-specific data, route meteorological conditions, air services restrictions, and air traffic management, as listed below:

- Taxi fuel, which is the fuel amount expected to be consumed before take-off. It considers local traffic flow regarding the time, taxi distance from and to the terminal, and, if applicable, fuel consumption by the auxiliary power unit (APU).
- Fuel for the destination airport must be the fuel amount required from take-off, or the in-flight re-clearance point, until landing at the destination, considering the aforementioned operational conditions.
- Contingency fuel, which should be the amount of fuel required to compensate for unforeseen factors. This amount must be 10% or 5% of the fuel needed to fly from the airport of origin to the destination, depending on the operator type of approval.
- Fuel for the alternative destination aerodrome.
- Final reserve fuel, which in the case of jet aircraft should be sufficient to fly for 30 minutes at holding speed at 1500 feet above aerodrome elevation in standard atmosphere condition.

- Additional fuel, which must be the extra amount of fuel required to allow the aircraft to descend as necessary and proceed to an alternate airport in the event of an engine failure or depressurization, which requires an amount of fuel assuming that the failure occurs at the most critical point in the route.
- Discretionary fuel, which must be the amount of extra fuel to be carried on board at the pilot-in-command choice. Meteorological information at an arrival airport is one of the primary variables used to determine refueling of discretionary fuel (Kim et al., 2021).

Airlines have limited capacity to optimize the minimum required fuel planning, as it is defined by regulation. Therefore, the focus should be on reducing the amount of discretionary fuel dispensed unnecessarily due to excessive conservatism, without however compromising safety (Ryerson et al., 2015).

Norén, P. (2009) pointed out that airlines spent 10% more fuel than necessary. According to Ryerson et al. (2015), 4.48% of the fuel consumed by an average flight is due to unused fuel loading. Additionally, another 1.04% is the result of contingency fuel uplifted above a reasonable safety margin. In order to illustrate the magnitude of the problem, only one major US airline burned 467 million pounds of kerosene and emitted 1.46 billion pounds of CO_2 into the atmosphere to carry unusable fuel during one year of operation (Ryerson et al, 2015).

Considering that airlines are transporting more fuel than they actually need, weather forecasting could play a crucial role in improving the flight planning efficiency. Aeronautical operations are susceptible to meteorology. Reliable information about weather conditions can ensure the safety of flights, as well as decreasing costs by reducing the amount of fuel to what is strictly necessary (Anaman, 2017).

Leigh et al. (1998) pointed out that airlines have adopted measures to increase profit margins. One of them is the use of high-quality meteorological information to reduce the amount of fuel, without sacrificing safety.

Terminal aerodrome forecasts (TAFs) are the most widely used meteorological product for flight planning purposes (Mahringer, 2008). According to Anaman et al. (2000), some airlines have opted not to add extra fuel due to possible adverse weather conditions with reliable, accurate TAF information. This measure is applied when the forecast indicates a lack of unfavorable conditions at the destination airport.

As noted, several studies demonstrate the importance for more efficient flight planning. The target is to reduce fuel on board and consequently burning fuel. The influence that weather forecast exerts on this process is also known and widely discussed. However, little or no reference is made regarding flight planning when a low probability forecast of significant weather occurrence is predicted for the landing time.

Weather Forecast Accuracy

Meteorology is one of the most critical areas for aviation. Its study and observation are fundamental for flight safety. Improving the accuracy of weather forecasts is therefore a major goal for the aviation community (Klein, 2017). From an operational point of view, airport weather is available from METAR and TAF and their derivatives, such as SPECI, for aircrews. However, several instruments are needed to arrive at these messages in a few lines with a detailed description of the local atmosphere. These instruments can be placed on the ground, at altitude, or even in orbit.

Since its implementation, the Brazilian airport infrastructure presents obstacles related to politics and economics that hinder operations at large airports (Braga, 2019). These difficulties, in turn, result in delays and flight cancellations. Among the probable causes for these occurrences, adverse meteorological conditions should be highlighted.

In Brazil, there is a network of meteorological stations that are classified, according to their characteristics, in Surface Meteorological Stations (SMS) - classes I, II, and III; Altitude Weather Stations (AWS) and Weather Radar Stations (WRS).

Surface Meteorological Stations (SMS) perform the collection and processing of meteorological information at the surface level. They are installed at aerodromes as part of the World Meteorological Organization (WMO). They are responsible for producing METAR, SPECI, and SYNOP messages (REDEMET, 2015).

Altitude Meteorological Stations (AMS) perform the collection, through radiosonde, of pressure, temperature, humidity, wind direction, and speed data, at different levels of the atmosphere, using weather balloons, as shown in Figure 7 (REDEMET, 2015).

The Meteorological Radar Stations (MRS) carry out constant surveillance in the area covered by the radars and disclose the information obtained through fast and reliable means to the Meteorological Surveillance Centers (REDEMET, 2015).

Safety Considerations

Efficient flight planning must be performed within the highest safety standards. Aircraft safety during flights can be affected by weather-related hazards. Most of the time, these hazards are the result of fog, turbulence, thunderstorms, and wind shear.

These hazards are the causes of many reported airline accidents around the world (Malala, undated).

According to IATA, the air transport industry plays a significant role in the global economy and development. Aviation is a key driver of global economic development. Over a third of all trade by value is sent by air, which makes aviation a key component of business worldwide (ATAG, 2021). One of the critical elements to maintaining civil aviation is to ensure safe, secure, efficient, and environmentally sustainable operations.

Two factors should be highlighted that contribute to the efficiency of safety and infrastructure of air operations in Brazilian commercial aviation:

1. The privatization of airports, which began in February 2012. Furthermore, with regular operations, they have been privatized in recent years. As a result, the number of passengers has jumped from 53.9 million in 2000 to 175 million in 2013. Privatization has substantially improved the entire airport infrastructure with better runways and taxiways, current navigation aids, and an improved air traffic management system (ITA, 2021).
2. The advent of the Global Navigation Satellite System (GNSS) in 1991. With that, the primary navigation method started to use this new system type which improved safety during all phases of flight. GPS is a critical component of a safe and efficient air transportation system (ALPA, 2012). GPS will be good enough to use as a standalone GNSS for applications such as enroute navigation (Kovach, 1998).

According to ANAC (2020), airlines operating under the rules of RBAC 121, Section 121.349 establishes the need for authorization, through the Operating

Specifications, of any GPS system used to meet the requirements of navigation equipment.

Many airports that served regular aviation had non-precision approach procedures. Currently, there are two types of instrument approach: precision approach (PA) and non-precision approach (NPA). In contrast to PA where both lateral and vertical guidance has to be provided, NPA provides only lateral guidance (Rao et al., 2001). Naturally, all these systems have their distinct pros and cons. One common disadvantage of NPA is its low range. This is due to the curvature of the Earth. In addition, there is the high cost, due to the requirement of high robustness and availability of the air navigation service (Frischauf, 2014). With GPS procedures in practically all these airports in the national territory, we gained efficiency on all operations. Precise approaches provide lower weather minima, being much more accurate and safer. Global Navigation Satellite System (GNSS) offers the advantage of operating under all weather conditions, with high temporal and spatial resolution and high accuracy (Isioye, 2015).

A very important factor related to aviation safety is the trip amount of fuel (Drees, 2017). Concerning managing fuel quantity during a flight, the airline should monitor the weather progress through meteorological bulletins. It is vital to check destination and alternatives TAF and METAR constantly. If such information is not available, meteorological messages should be sought from nearby airports. They are a valuable source of information to aid in decision making process of setting required fuel.

The calculation of fuel requirements is one of the most critical aspects of flight planning both in terms of safety and cost (AEAT, 2008). The industry already adopts a standard amount of reserve fuel during flight planning practices. This quantity varies from 5% to 10%. The in-flight reclearance method can be established when the minimum reserve fuel can not be carried.

Reclearance procedures are a common practice to reduce the permissible minimum amount of reserve fuel (AEAT, 2008). A reclearance flight is initially planned to an airport closer than the final destination. This procedure takes advantage of the fact that a large portion of the required reserve fuel is dependent on range. If sufficient fuel is available at a specific decision point, the flight can be “redirected” to the final destination (AEAT, 2008). All these methods are intended to implement different analysis possibilities for determining the amount and need for reserve fuel.

Summary

Airlines are interested in finding the optimal/minimum amount of fuel for their operation due to the large proportion of fuel costs on the total airline costs. Furthermore, weather forecasts directly affect flight planning.

The amount of fuel to be planned for each flight stage takes into account several factors. However, the subjective analysis of the amount of reserve fuel varies according to the intensity and probability of meteorological phenomena.

Obviously, a weather forecast is meaningless when it is not accurate. Accuracy is translated into factual verification of what was planned and what actually happened. Thus, this factor is directly linked to the infrastructure capacity of the Brazilian meteorological forecast system.

Safe flights come as a result of all these factors. The correct interpretation of meteorological products, as well as their relevance, affects the outcome and performance of the journey. Economic efficiency, sustainability, and safety are only achieved when these viewpoints are considered.

A policy of disregarding extra fuel on flights with PROB 30 and PROB 40 generates a misinterpretation of being negligent and unsafe. This research study focused on improving the operational fuel efficiency of the processes adopted today in the industry for dispatching flights, as well as creating suitable risk management matrices for eventual implementation.

Chapter III

Methodology

This study aims to observe the impact and the effects caused by adverse meteorological events when there is a low occurrence probability (PROB 30 and PROB 40). The paramount intention is to check the need for extra fuel supply.

This chapter intends to demonstrate how the research was conducted. It brought information about the nature and type of data used. In the same way, it illustrated how the data were structured and examined.

Sampling Design, and Data Collection

This study centralized and analyzed flights with destination to São Paulo Congonhas Airport (CGH - IATA Code). To compose the flight pairs, eight origin airports were chosen: Rio de Janeiro - Santos Dumont (SDU), Rio de Janeiro – Galeão (GIG), Brasília (BSB), Belo Horizonte – Confins (CNF), Curitiba (CWB), Florianópolis (FLN), Porto Alegre (POA), and Salvador (SSA).

Figure 2 – Flight Pairs Sample Visualization

The flight information was obtained from a major Brazilian airline. This database was collected through the system known as Fleet Movement. It controls all flight operations. This method is updated almost in real-time either by the Aircraft Communication Addressing and Reporting System (ACARS) or throughout operational links fed by company airport bases.

The sample size of the flight database comprehended 24.040 flights. All of them were performed in 2019. For the purposes of this study, data relating to selected flights were collected including:

- Trip Fuel Planned
- Trip Tank Based Fuel
- Additional Fuel Planned
- Hold Fuel
- Estimated Departure Time – Date Time
- Estimated Arrival Time – Date Time
- Actual Departure Time – Date Time
- Actual Arrival Time – Date Time
- Origin Airport – String
- Destination Airport – String
- Flight Time – Time
- Block Time – Time
- Delayed On Departure – Boolean
- Delayed On Arrival – Boolean
- Delay Codes – String

For this research, the weather data was collected in the database of the Brazilian aeronautical meteorology network (REDEMET). The Meteorology Network (REDEMET) is the channel used by DECEA to provide meteorological data for civil and military aviation. REDEMET maintains cooperation with several national and international bodies of Aeronautical Meteorology and is the official means of the Aeronautics Command (COMAER) to disseminate this information. The sample size included all TAFs and METARs issued in 2019, for all the selected airports related to this study. These airports are provided with facilities capable of generating observation data. Forecast data are created by the aeronautics meteorology centers (CMA).

Procedures, and Data Analyses

To compile the study information and organize the data, it was generated tables for data analysis. TAF are forecasts generated every 6 hours (00:00, 06:00, 12:00 and 18:00 - Greenwich time) and have their description understood for the next 24 hours. However, this study considered only the first 6 hours as the effective validity of the information, that is, the message was considered expired whenever a new meteorological product was issued. The METAR is issued every hour (and comprehend one hour observation), so all information was considered. According to the validity of the beginning and end of each meteorological event, 13.140 TAF and 78.840 METAR messages needed to be secreted and interpreted.

After that, all TAF were decomposed into message blocks in order to search and identify the existence of adverse weather events probabilities. For the extraction and decoding of TAF messages, the following diagram was used:

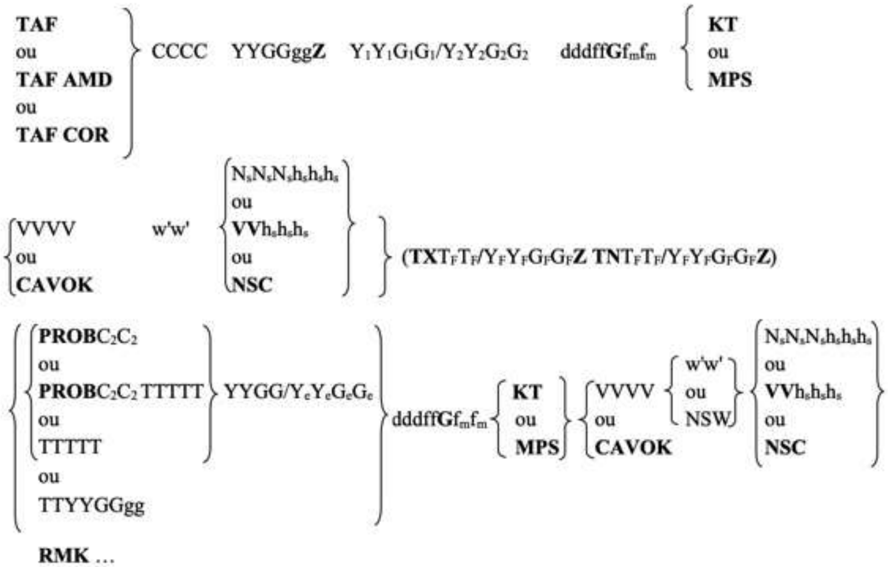

Figure 3 – TAF Blocks Diagram

Below, an example that make it easier to understand the extraction of occurrences:

TAF SBCT 101030Z 1012/1112 24003KT 9999 SCT015 TX28/1018Z TN20/1109Z TEMPO 1018/1024 4000 +TSRA BKN010CB ***PROB40 TEMPO 1020/1022 TSRA***

In the example, the TAF shows a 40% probability of occurrence of a thunderstorm with moderate rain, in the period 2000 to 2200 UTC.

At Table 2 (see below) the predicted phenomenon is coded and the inclusion of them was performed by using the events abbreviations letters. We searched within the extracted part for the following meteorological phenomenon codes: TS, SH, RA (any intensity).

Table of Significant Present, Forecast and Recent Weather				
Qualifiers		Weather Phenomena		
Intensity or Proximity	Descriptor	Preciptation	Obscuration	Other
"-"= Light	BC - Patches	DZ - Drizzle	BR - Mist (≥5/8SM)	DS - Dust Storm
No Sign = Moderate	BL - Blowing	GR - Hail	DU - Widespread Dust	FC - Funnel Cloud
"+"= Heavy	DR - Drifting	GS - Small Hail/ Snow Pellets	FG - Fog (<5/8SM)	+FC - Tornado or Waterspout
"VC"= Vicinity	FZ - Freezing	IC - Ice Crystals	FU - Smoke	PO - Well developed dust or sand whirls
	MI - Shallow	PL - Ice Pellets	HZ - Haze	SQ - Squall
	PR - Partial	RA - Rain	PY - Spray	SS - Sandstorm
	SH - Showers	SG - Snow Grains	SA - Sand	
	TS - Thunderstorm	SN - Snow	VA - Volcanic Ash	
		UP - Unknown Precipitation in automated observations		

Table 2 – Significant Present, Forecast and Recent Weather

After the TAF weather events were decoded, a dispatch schedule was created for each flight. This time was obtained by subtracting 1 hour and 30 minutes from the planned departure time for each sample. This specific timetable was contrasted with the last valid TAF existing for the destination airport. Among the valid blocks of events for this pointed forecast, was performed a search for probability codes of relevant meteorological phenomena. This search was based on the planned arrival time at the destination aerodrome.

Once this was done, to enable the analysis of the accuracy of the forecasts issued in the TAF messages, it was necessary to cross-check this information with the meteorological observation found in the METAR (for the planned arrival time). This crossing of information allowed measuring the percentage of meteorological forecasts from the TAF that are confirmed in the METAR. Through this procedure it was possible to identify the percentage of flights that actually encountered the meteorological phenomenon foreseen in the dispatch TAF. In the same way, this verification made it possible to isolate flights that have really being affect by meteorological events on their landing time. For a better understanding of the formatting established in this analysis, a flowchart was created as shown in the figure below.

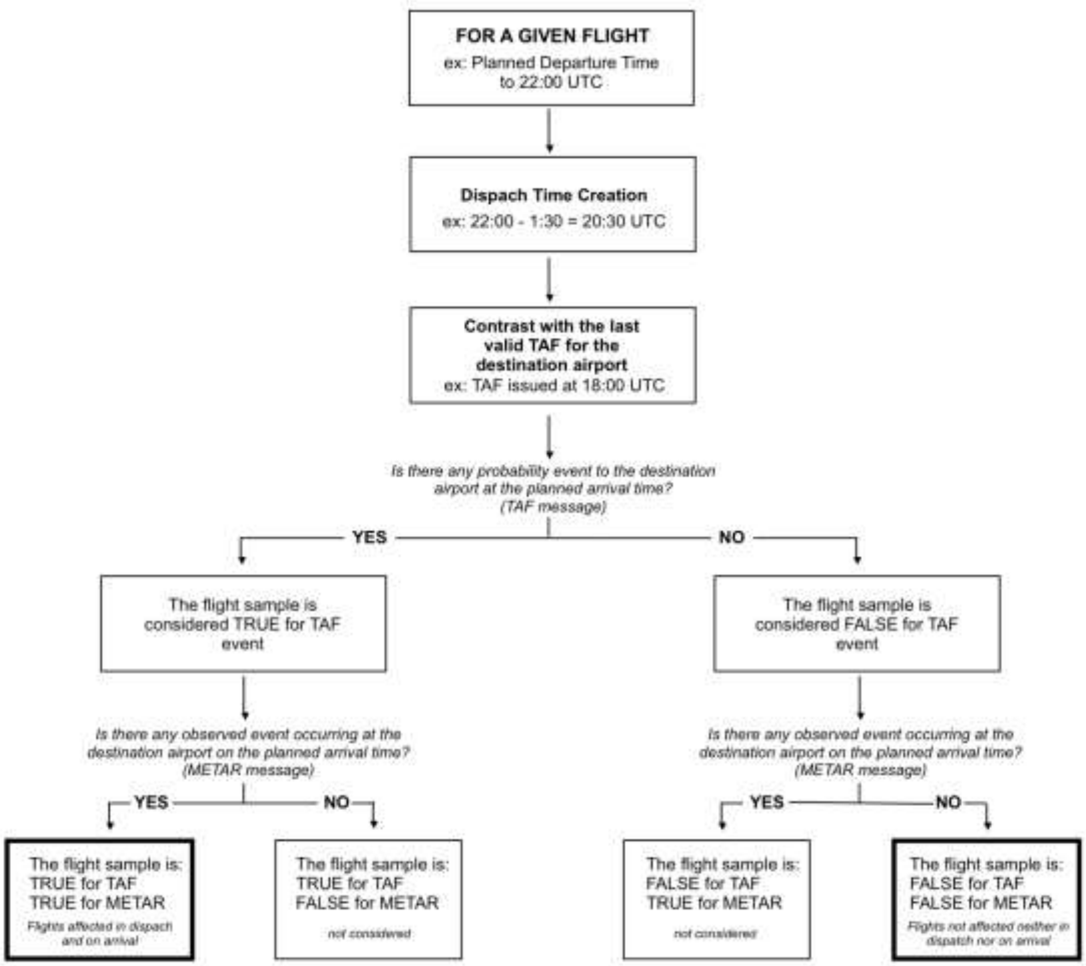

Figure 4 – Statistical Analysis Flowchart

To validate the accuracy of the weather forecasts, the group decided to use the bias exclusion technique. The occurrence of an observed phenomenon or unobserved phenomenon is the possible result to be found. In this way, groups have been created to further analysis. The study focused on the contrasting significance between flights samples that are TRUE for TAF and METAR (with event effect, called TRUE TRUE) as opposed to flights samples that are FALSE to TAF and METAR (with NO event effect, called FALSE FALSE).

For each origin-destination category, two-independent samples t-tests were generated (respecting each case proper sample variance) trying to observe statistical significance among samples flight times (TRUE TRUE versus FALSE FALSE). The null hypothesis states that there is no difference between flight time means. We selected a significance of 5% to prove the alternative hypothesis (where there are difference on flight time means).

Descriptive and distributive analysis of the data were also carried out in order to understand its structure. These checks were made both for flight time between those affected and unaffected, as well as for fuel consumption. In this last case, the fuel planned for the trip was opposed to the real consumed in the studied flight.

The research group used the Python program to extract, manipulate, and analyze the data in this project. Python is a program with an open-source programming language, with high-level performance, easy to learn, and with a vast online community. As this research involved a large volume of data manipulation, choosing a language capable of performing all this processing was fundamental.

Limitations

This study found limitations in data consistency by correlating the planned TAFs the arrival observed meteorological condition. It is since more than one TAF is issued at the same time. The closer the forecast time, the more accurate is the phenomenon possibility. In this way, the analysis had to consider only 6 hours of validity for each TAF. As the next one was issued, the last one was dismissed. In the same way, it was used the arrival planned time to select the METAR observation, trying to minimize the possibility of in-air holding time that could annul the event on actual arrival time.

Another limitation found was related to the meteorological phenomena codes. Researchers had to create patterns of similar weather conditions because even with different terminologies, the subjectivity in the ideal of predictability was identical.

Any extreme outliners were disregarded due to the possibility of extra variables influences. In the same way, data resulting as blank cell on data sheet has also been discarded, because it could not be possible to certificate the correct value for that example.

Finally, it was challenging to determine the correlativity of flight time dilation. Even when observing the existence of meteorological events, it was not possible to certify the exclusion of the influence of air traffic management for a given sample.

Summary

To analyze the effects and impacts of low-probability weather forecasts (PROB 30 and PROB40), the researchers conducted a two-step study. At first, the weather information has been decoded. Then, they were contrasted with the planning and execution of the flights in order to produce an existence-of-effect relationship. The occurrence of an observed phenomenon or unobserved phenomenon is the possible result to be found.

The meteorological data were collected from the REDEMET database, which is the official meteorological information dissemination channel of the Brazilian airspace control department. The flight information was obtained from the database of a Major Brazilian Airline.

To validate statistical significance, two-independent samples t-tests were generated. As well as descriptive and distributive analyzes regarding flight time and fuel consumption.

For data manipulation and analysis, the researchers used Python software. This tool was chosen because it is an open-source programming language, with a high data processing capacity.

Chapter IV

Conclusions

This research project aimed to evaluate the accuracy of significant weather forecasts with low probability of occurrence (PROB 30 and PROB 40), as well as its real effects and impacts on flight operations. The main objective was to determine the correct amount of fuel to be planned when there is such a forecast.

To reach their conclusions, the researchers collected a large sample of meteorological and flight data for the year 2019. These data were worked with the help of dedicated software. Once the information was organized, the group conducted a series of analyzes and statistical procedures in order to reach the final considerations.

- **Conclusion One**

  i. **Data getting:**

     The researchers obtained the meteorological data through the national product emission network (REDEMET).

  ii. **Results:**

     29,21% of predicted phenomena had occurrence observed.

  iii. **Conclusion:**

     The probabilistic effect of weather forecasts has its mathematical occurrence confirmed.

- **Conclusion Two**

  i. **Data getting:**

     The researchers obtained the data through flight data monitoring systems from a Brazilian major airline.

ii. **Results:**

In the statistical calculations, all samples presented rejection of the null hypothesis.

iii. **Conclusion:**

All samples presented statistical significance.

- **Conclusion Three**

i. **Data getting:**

The researchers obtained the data through flight data monitoring systems from a Brazilian major airline.

ii. **Results:**

Flight time increment of 6 minutes on the samples with the presence of the meteorological effect.

iii. **Conclusion:**

Predicted weather on arrival (also confirmed at the landing hour) affected its trip time flights' sample. The mean increment observed on influenced flights was 6 minutes.

- **Conclusion Four**

i. **Data getting:**

The researchers obtained the data through flight data monitoring systems from a Brazilian major airline.

ii. **Results:**

An average fuel consumption increment of 141 kg on the samples with the presence of the meteorological effect.

iii. Conclusion:

Predicted weather on arrival (also confirmed at the landing hour) affected its fuel consumption flights' sample. The mean increment observed on influenced flights was 141 kilograms.

Final Considerations

It was possible to observe the accuracy capability in weather forecasts that count on low probability adverse weather effects. Based on the result of the separation of flights into groups, different samples were obtained. Contrasting the group that had events in the flight planning, however, without observing these on arrival (TRUE/FALSE) with the group that also found positive planning as well as events on arrival (TRUE/TRUE), it was possible to conclude the accuracy percentage of the predictive capacity.

Origen	Destination	Total	False - False	True - False	True - True	Accuracy
SDU	CGH	6798	5863	718	217	30,22%
BSB	CGH	3210	2824	298	88	29,53%
POA	CGH	3279	2839	339	101	29,79%
CNF	CGH	2522	2209	252	61	24,21%
CWB	CGH	2230	2012	166	52	31,33%
FLN	CGH	1718	1481	182	55	30,22%
GIG	CGH	2420	2146	204	70	34,31%
SSA	CGH	1863	1652	170	41	24,11%
				Accuracy Mean		**29,21%**

Table 3 – Data Accuracy

All statistical calculations brought significance to the results. The null hypotheses for all the examples that were studied were rejected. It translates into proof that the sample means are statistically different. Thus, it can be concluded that some factors and variables affect both samples regarding flight time and fuel consumption.

	TIME		FUEL	
Flight Pair	***pValue***	**Result**	***pValue***	**Result**
BSB-CGH	5,16E-07	Rejected	5,42E-04	Rejected
CNF-CGH	0,00095	Rejected	0,03275	Rejected
CWB-CGH	0,00019	Rejected	0,00018	Rejected
FLN-CGH	8,09E-05	Rejected	6,32E-08	Rejected
GIG-CGH	2,14E-07	Rejected	5,22E-10	Rejected
POA-CGH	1,56E-08	Rejected	7,872E-05	Rejected
SDU-CGH	1,78E-13	Rejected	1,332E-40	Rejected
SSA-CGH	4,86E-03	Rejected	6,024E-08	Rejected

Table 4 – Statistical Analysis Results

The average extension flight time was found by subtracting the values of the sample that found a meteorological effect from the one that did not have this incidence. For this purpose, an average per group was calculated, resulting from the arithmetic division of all flight times of the units studied in the specific set. Finally, the suggested flight average was obtained from the arithmetic division of all the final averages found for each group with significant meteorological effects.

TRIP TIME

Flight Pair	Mean False (x̄f)	x̄f time	Mean True (x̄t)	x̄t Time	Difference
BSB-CGH	1,349728132	1:20	1,462310606	1:27	0:07
CNF-CGH	1,019710014	1:01	1,108469945	1:06	0:05
CWB-CGH	0,704700216	0:42	0,808496732	0:48	0:06
FLN-CGH	0,850011254	0:51	0,974242424	0:58	0:07
GIG-CGH	0,836812675	0:50	0,953095238	0:57	0:07
POA-CGH	1,24860621	1:14	1,350660066	1:21	0:07
SDU-CGH	0,778113444	0:46	0,882411674	0:52	0:06
SSA-CGH	2,22946933	2:13	2,338211382	2:20	0:07
				x̄ Difference	0:06

Table 5 – Trip Time Analysis

For each studied example of origin and destination, it was observed which was the highest extra fuel consumption situation. Given this, all samples with meteorological effects on arrival had their fuel consumption increased. In this way, this specific group was isolated and considered. Finally, an arithmetic average was generated between these groups. An approximate 141 kg result of additional fuel was consumed on flights that encountered meteorological phenomena on arrival.

FUEL

Flight Pair	Mean False	Mean True	Extra Consp
BSB-CGH	91	166	166
CNF-CGH	3	98	98
CWB-CGH	-94	86	86
FLN-CGH	-74	63	63
GIG-CGH	-62	182	182
POA-CGH	14	130	130
SDU-CGH	-49	130	130
SSA-CGH	95	272	272
		Extra Consp.	141

Table 6 – Fuel Consumption Analysis

Chapter V

Recommendations, Future Research, and Lessons Learned

The study's main objective was to determine whether there was a need to add extra fuel in the flight planning when there were low probability weather forecasts (PROB 30 and PROB 40) at the estimated landing time. A large sample of both meteorological and flight data was collected and analyzed.

After the analysis, the researchers reached the following conclusions:

- 29.21% of the meteorological phenomena foreseen in the TAFs with PROB 30 and PROB 40 materialized.
- The samples of flights with the occurrence of meteorological phenomena had an average of 6 minutes of dilation in the flight time when compared to samples without observation of the phenomena.
- It was found an average increase of 141Kg in fuel consumption in-flight samples with meteorological phenomena presence compared to samples where such effects were not observed.

Recommendations

Carry out an in-depth analysis of each specific destination in order to determine the ideal amount of extra fuel to be added in the flight planning when there are low probability weather forecasts (PROB 30 and PROB 40) in the TAF in question.

Background

Making fuel supply recommendations by establishing metrics and parameterizing quantities is a delicate task. It is because each destination airport has its peculiarities. It must be noted that the search for a metric involves further calculations and safety assessments. The additional analysis should consider the potential of the risks involved, which may be acceptable respecting each specific destination.

That said, based on the description of the data analyzed in this study, our recommendation is not focused on a specific numeral denominator but rather on highlighting the great possibility of efficiency gains in flight planning. We strongly believe, from the conclusions we have reached, in the existence of a causal relationship. However, further studies must perform a deeper analysis of each destination for a specific quantitative recommendation.

Limitations of the study

- The study was done for arrival at a single airport (CGH).
- Difficulty in excluding the bias of the possibility of air traffic management influence in-flight time dilatation.
- The analysis was made considering a single meteorological phenomenon (Rain).

Future research

- Extend the study to other operated airports.
- Prolong the study to other meteorological phenomena, such as fog, for example.
- Conduct a comparative study between the cost of a diverted flight and the savings generated by taking less fuel on board.

Lesson learned

- Confirmation of 29.21% accuracy of PROB 30 and PROB 40 in TAFs;
- During the project, we came across several possibilities to improve the metrics used in flight planning.

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