IT-SUPPORTED DATA ANALYSIS OF FUEL CONSUMPTION AND FLIGHT PROGRESS IN THE AVIATION SECTOR

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KEYWORDS

Fuel Costs, Aviation Emission, Data Analytics, Excel, MATLAB.

ABSTRACT

Aviation continues to be an important means of transport for passengers and cargo. However, fuel savings and emissions reduction have become increasingly important in recent years. As part of a PhD thesis, possibilities for reducing fuel consumption by reducing the final reserve fuel were investigated. A smaller amount of fuel required leads to a reduction in the transported (fuel) weight and thus to a reduction in fuel consumption. Improved risk assessment, calculations based on better data (e. g. aircraft performance, route and weather) and better decision-making provide an enormous potential to optimise the amount of fuel needed without compromising safety levels. Proof of this must be provided with the help of suitable data collection, often with correspondingly large data sets. The statistical basis for this study was data over a five-year period provided by an airline from various reports, each with approx. 40 000 data sets. The assessment was carried out in several steps using various tools such as Excel or, in particular, MATLAB. A wide range of data on all aircraft movements is recorded in the internal database system of the air carrier which provided the information. Be means of statistical analysis of existing fuel data, it was possible to prove that the planning and flight execution is reliable - as a representation of the basic level of safety. MATLAB provides a quick way to create clear and meaningful plots. With the help of this assessment, evidence of a performance-based approach to the approval of fuel planning procedure can be provided. This in turn can be used for the application of procedures requiring approval by the competent authority.

INTRODUCTION

Fuel costs are a driver for reducing the amount of fuel consumed. In recent years, however, increasing attention has also been paid to environmental impacts. Reducing the effect of global warming due to emissions has become an important target. An often-mentioned goal is to reduce global net aviation-created emissions by 50% till 2050 compared to 2005 (IATA, 2019). As a result the reduction of emissions has become a major concern. Both aspects will be briefly discussed in the following.

Fuel Costs

Despite a downturn in 2020 and 2021, aviation is expected to recover to pre-pandemic levels. Already in 2015, around 3.5 billion passengers used air transport for their business and tourism purposes. This is an increase of around 6.4 % compared to 2014 (ICAO, 2016). For 2037, an IATA forecast predicts the number of air travellers reaching 8.2 billion (IATA, 2018). The industry is facing major challenges at the same time. Emissions from aviation, both domestically and internationally, account for account for about 2% of total global CO_2 emissions (ICAO, 2014). Fuel prices are linked to crude oil prices and are therefore volatile. Figure 1 (Airbus, 2014) shows the price development over a period of more than a decade. The fundamental upward trend can be seen, which has radically intensified in spring 2022.

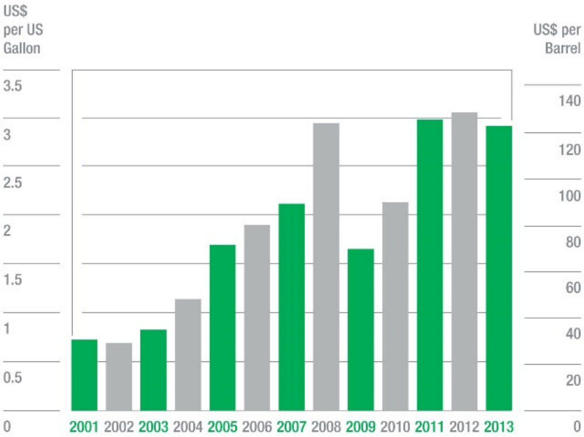

Figure 1: Monthly Jet Fuel Price Trend

The price is influenced by various factors such as political instability or high demand. Publications by International Air Transport Association (IATA) also show this trend, although a drop below $35 per barrel can also be seen here in spring 2020. In spring 2022, prices have developed to over $155 per barrel, according the IATA Jet fuel price development (IATA, 2021). As a consequence fuel consumption and the associated costs represents a significant part of operating costs, see Table 1 (Airbus, 2014).

Table 1: *Direct* Operating Cost *Breakdown*

Cost factors	Share of costs [%]
Crew	18
Maintenance	25
Fuel	28
Navigation/Landing	24

Airline fuel expenditure varies from more than 30 per cent in 2012 to around 20 per cent in 2016, and has been projected to reach around 28.4 per cent of total expenditure in 2020. In 2021, it amounted to 19 per cent of total expenditure (Statista, 2022). As crude oil prices rise in 2022, the share of fuel costs is expected to move back towards the 2014 ratio.

Emission Reduction

The effects of global warming have been increasingly observed in recent years, leading to efforts to limit this effect. An often mentioned goal is to stabilise the temperature increase to below 2°C compared to pre-industrial levels (Intergovernmental Panel on Climate Change, 2015). 30% of all transport-related CO_2 emissions are caused by combustion (International Transport Forum, 2020). In 2022, almost every commercial aircraft is still equipped with a fossil fuel-based propulsion system. Alternative propulsion systems, such as the use of liquid hydrogen (LH_2), are intended to make aviation more environmentally friendly, but are not yet sufficiently available (Janić, 2014).

The most important emissions from aircraft are greenhouse gases and noise. The results of jet fuel combustion consist mainly of carbon dioxide CO_2, water vapor H_2O, methane and nitrous oxide NO_x. The Intergovernmental Panel on Climate Change (IPCC) notes that CO_2 and H_2O are simply the most common products of jet fuel combustion (Intergovernmental Panel on Climate Change, 1999). Their emission indices are 3.15 kg/kg fuel burned and 1.26 kg/kg fuel respectively (Intergovernmental Panel on Climate Change, 1999). For NO_x the IPCC constitutes that it is next most abundant engine emission. The range of NO_x emission is between 5 and 25 g NO_x per kg of fuel burned (Intergovernmental Panel on Climate Change, 1999). In addition to the emissions mentioned above, there are other factors such as water vapour, soot and sulphate aerosols and increased cloud cover due to the formation of contrails (Lee et al., 2020). Contrails, their formation and possible effects are an equal special part of aviation research. Fuel costs and the impact of aviation on the environment have become increasingly important. In particular, reducing the impact of global warming due to emissions has become a goal. The commercial aviation industry has already developed and implemented many techniques to reduce fuel consumption for reasons of economy and cost effectiveness. However, further efforts are necessary.

FUEL SAVING VIA WEIGHT REDUCTION

An important consideration in optimising fuel consumption, whether for the future or current operations, is the weight of aircraft and equipment. It is the physics of flight, that for an aircraft to fly it must generate lift to overcome its weight. The generation of the required lift and the movement of the airframe through the air create drag. The engines generate the necessary thrust to overcome this drag and enable the movement to generate lift, see Figure 2 (Airbus, 2014).

Figure 2: Elementary forces on an airframe

Fuel consumption for a given route therefore depends, among other factors, on the weight of the aircraft. The more an aircraft weighs, the higher the fuel consumption. To keep fuel consumption as low as possible, it is most economical to carry only the minimum weight required for the route in question. Carrying more or even unnecessary weight increases the amount of fuel required and consumed in flight.

The fuel consumption, for carrying extra weight or extra fuel, is called Fuel Carriage Penalty (FCP). European Union Aviation Safety Agency (EASA) gives a value of about 3 % extra in fuel consumption per kg and flight hour for additional weight (EASA, 2016). International Civil Aviation Organization (ICAO) Doc 10013 gives a value of around 2.5 - 4.5 % additional fuel consumption, depending on the characteristics of the aircraft (ICAO 2014, p. 12). Ayra et. al mentions a value of up to 4 % additional fuel consumption per flight hour to cover additional weight. Thus, for a seven-hour flight that fills up with 5 000 kg of extra fuel, about 1 300 kg of this fuel is consumed just to carry it. For the aircraft investigated in the study, the factor is 0.0273 kg fuel per flight hour per kg additional weight.

As a result, excessive fuel consumption has a significant impact on a company's environmental impact and profit

(Ayra et al., 2014). Note: the economic influence of fuel prices, which play a role in the context of fuel tankering, is not considered here. Conversely, Ayra et al. mention the potential benefits of fuel savings. A 1% reduction in consumption would save about 100 tonnes of fuel per year for a medium-sized jet aircraft. This amount corresponds to an approximate annual cost reduction of €38 000 per aircraft (Ayra et al., 2014). The associated emission reduction for a medium-sized aircraft can be calculated from the above figures. At 100 tons of fuel, this would be 315 tonnes of CO_2, 126 tonnes H_2O and between 500 and 2 500 kg NO_x per aircraft per year. This effect clearly states the profound saving potential of a reduction of fuel unnecessarily being carried on board.

LEGAL FUEL REQUIREMENTS

Looking for aviation regulations, the ICAO is the first organisation that comes to mind on an international level. Founded in 1944, ICAO is a specialized agency of the United Nations. One of ICAO's objectives is to promote the safe and orderly development of international civil aviation. At the global level, ICAO establishes standards and recommended practices (SARPs) covering aviation safety, security, efficiency, economic development, and environmental protection. ICAO is developing the Global Aviation Safety Plan (GASP) and the Global Air Navigation Plan (GANP), both globally planned initiatives in the area of safety and air navigation services (ICAO, 2016). ICAO publishes various documents with different legal force. One are the Annexes to the Convention on International Civil Aviation in accordance with Article 37 of the Convention on International Civil Aviation. An Annex of significance to commercial aviation is Annex 6. Chapter 4 of Annex 6 contains requirements for flight operations, with subchapter 4.3 listing SARPs for flight preparation. Subchapters 4.3.6.1 and 4.3.6.2 require that, based on actual aircraft-specific data and operating conditions for the planned flight, a sufficient quantity of usable fuel is carried to safely accomplish the planned flight and to allow for deviations from planned operations (ICAO, 2018). ICAO SARPs are not directly binding, they have to be transposed into national law.

At the European Union (EU) level, the scenario is slightly different. Aviation regulations are developed by the EASA. EASA develops different levels of regulatory material. The EU itself knows different types of legal acts. Regulations, decisions and opinions are relevant for the aviation sector. Regulations have a binding effect throughout the EU. Decisions are binding for an EU country or an individual operator. EASA Opinions are not binding, they allow a statement (European Union, 2020). Regulation (EU) No. 965/2012 sets out the requirements and procedures for air operations.

Due to changes in Regulation (EU) No. 965/2012, which will apply from fall 2022, there was an adjustment in the fuel requirements. These were previously regulated in CAT.OP.MPA.150, among others, and will in future be referred to in CAT.OP.MPA.180 and the following sections (EASA, 2020b). Operators demonstrating certain capabilities will be able to use individual fuel schemes in the future. This is intended for operators who can demonstrate a defined safety level, thus reflecting the move towards performance-based regulations (EASA, 2020b). Data supporting the intended deviation is required to support the implementation of the individual fuel scheme. The Annex to Opinion No. 02/2020 already contains preliminary information on the draft Acceptable Means of Compliance (AMC) and Guidance Manual (GM) and information to be considered for the performance-based deviation. A non-exhaustive list of safety performance indicators (SPI) that can be used to measure safety performance are:

- flights with 100 % consumption of the contingency fuel;
- flights with a percentage consumption of the contingency fuel (e.g. 85 %), as agreed by the operator and the competent authority;
- difference between planned and actual trip fuel;
- landings with less than the final reserve fuel (FRF) remaining;
- flights landing with less than minutes of fuel remaining (e.g. 45 minutes), as agreed by the operator and the competent authority;
- ‘MINIMUM FUEL’ declarations;
- ‘MAYDAY MAYDAY MAYDAY FUEL’ declarations;
- in-flight replanning to the planned destination due to fuel shortage, including committing to land at the destination by cancelling the planned destination alternate;
- diversion to an en-route alternate (ERA) aerodrome to protect the FRF;
- diversion to the destination alternate aerodrome; and
- any other indicator with the potential to demonstrate the suitability or unsuitability of the alternate aerodrome and fuel planning policy (EASA, 2020a).

As can be seen from these indicators, airlines wishing to have an individual fuel scheme approved by the competent authority require a great amount of data and information on fuel consumption.

EVALUATION WITH MATLAB

In order to check the reliability of the fuel planning and execution of the flights under the current requirements, corresponding information must be evaluated over a sufficiently long period of time - with the corresponding effort regarding the processing of the collected data. For further validation of the fuel data, real flight data of a globally operating European airline was chosen. For this purpose, data from a cargo airline was provided over a period of approximately 5 years (4 years and 10 months), from March 2016 to the end of December 2020. The aircraft used is a Boeing B777-200 in a cargo version. It has a maximum take-off mass of about 347 800 kg, a maximum landing mass of 260 800 kg and a dry operating weight of about 141 600 kg. This results in a maximum payload capacity of about 103 tonnes. The maximum fuel capacity for this version is about 144 024 kg. The route network served includes both major airports and some regional airports, resulting in a mix of short-, medium- and long-haul flights.

In the first step, the data was exported from the reporting system and analysed with Excel. This proved to be impractical for the reasons mentioned below. Therefore, MATLAB was used as a tool in the further steps.

Reporting System

For the data period provided, a large amount of flight information that can be evaluated via various reports was fed into the airline's data management system. This system collects and provides a variety of facts in different areas of interest, such as aircraft-related information, airport statistics, cosmic ray figures, crew data, on-time performance, and others. Flight information such as number of auto lands, information on city pairs, de-icing reports, delay reports, etc. are available as well. The data can be exported from the system in various formats, such as XML, Excel, PDF, MHTML, TIFF, Word or CSV.

With regard to fuel, the information is used, among other things, to compile statistics for the crews, for example as a decision-making aid for fuel planning. An electronic flight back (EFB) application is provided for this purpose. Specific fuel and flight information from 5 different reports was provided and analysable:

- Fuel Data Validation
- Dynamic Flight List
- Fuel Analyzer Reference List
- Fuel Analyzer App Data
- Flight List Uld Detail Load

In the first step of the analysis, the data was analysed with the help of Excel. For this purpose, the data was exported and corresponding statistical evaluations such as mean value, variance, etc. were carried out using Excel functions. This step was correspondingly time consuming. The examination of the 5 reports showed that they contain different quantities of data sets, respectively information. Missing data, wrong data or erroneous entries lead to such differences. Missing or wrong data can for example result from connectivity issues of the used aircraft communications addressing and reporting system (ACARS), miscalculation due to absent input, accidental operation of the ACARS system or simply missing information. Lost information, which may result in the rejection of a dataset, can be: previous fuel, fuel uplift, density, off- or on block time, shutdown fuel.

The different number of data sets within the reports did not allow to merge the information in one report. Sometimes information where only partially or only in one report available, potentially leading to false information.

Data analyses consist of some standard components: Pre-processing, summarisation and visualisation modelling. The pre-processing of the data for MATLB did not take place. Work was done directly with the exported data from the reporting system. Further investigations into, among other things, better data analysis with MATLAB are to be carried out, but are not part of this study. In the first step of the investigation, the visualisation possibilities of MATLAB were used.

In addition to the evaluation with Excel, which is time-consuming, the individual reports were therefore examined in MATLAB. For this purpose, the information from the reports, if applicable, was fed directly into MATLAB. For the analysis with MATLAB, the pure, unfiltered data from the reporting system was imported as a table via the Excel export used previously. No correction or adjustment of the data for incorrect, missing or erroneous entries took place in this step. Nevertheless, in the first step a quick evaluation was possible without the need for extensive MATLAB code. The following is an overview of the evaluations for the Dynamic Flight List Report and Fuel Analyzer App References List Report.

Dynamic Flight List

The Dynamic Flight List Report contains information on: date of flight, flight number, aircraft type, aircraft registration, departure airport, arrival airport, diversion information, scheduled and actual departure time (STD and ATD), scheduled and actual time of arrival (STA and ATA), expected departure time (ETD), expected arrival time (ETA), departure delay, airborne time, landing time, arrival delay, block time, flight time, scheduled time, flight status (scheduled, cancelled, departed, returned and arrived) and leg load. The Flight List Report contains information for 43 113 flights for the period 1st march 2016 till 31st December 2020.

The entries comprise 30 columns and 43 113 rows, i.e. a 43 113 x 30 matrix. Even after a brief examination of the data, almost 40 000 entries remained. 3 594 flights where marked as cancelled, meaning they were planned but did not take place. They were only considered in the comparison of planned and flown sectors. The resulting 39 519 flights took place. Out of that, 52 flights (0.13 %) returned on block after going off block. None of these flights went airborne. 6 flights, out of the remaining 39 467 flights, could be identified as have to be diverted, which gives a diversion rate of 0.015 %. The following information where extracted out of the Flight List Report:

- 43 113 flights, average planned block time 7:02 hours, flight time 6:20 hours
- 3 594 flights cancelled, average planned block time 7:23 hours, flight time 0 hours
- 39 467 flights arrived, average planned block time 7:00 hours, actual block / flight time 6:49 / 6:20 hours
- 52 flights returned, average planned block time 7:32 hours, actual block time 26 minutes

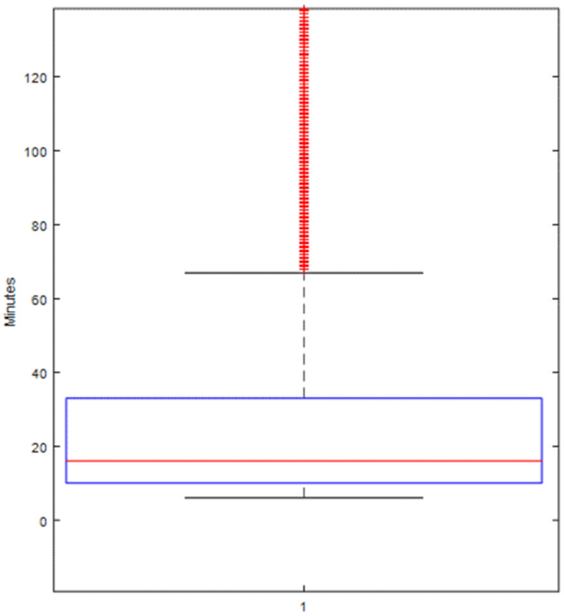

Figure 3: Arrival Delay

Delays in departures and arrivals are recorded in the Dynamic Flight List. Figure 3 shows a boxplot, created from the raw data over 43 113 flights, of arrival delays. Essential information on the boxplot are:

- Median: 16
- Maximum: 2 915
- Minimum: 6
- Number recorded: 43 113
- Finite Outliers: 703
- NaN or Inf: 36 915
- 75th percentile: 33
- 25th percentile: 10
- Upper adjacent: 67
- Lower adjacent: 6

As can be seen, the outliers drive the average upwards. Flights without delay have been recorded as Not a Number (NaN), in this case 36 915. In a more detailed analysis, special filters could be set to take a closer look at flights with delays of more than 60 minutes. The extreme value of 2 915 minutes should also be examined.

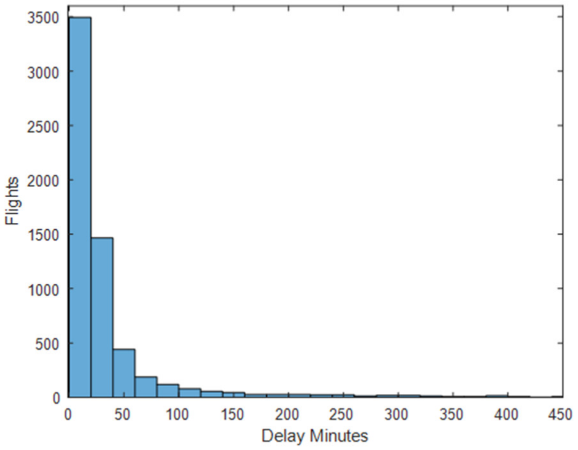

Figure 4: Delay Minutes

MATLAB offers the possibility to quickly create additional plots to the existing data. Delay information can also be displayed in a histogram for flights, where delays were recorded. Figure 4 shows the corresponding information. It can be seen that the majority of flights with delays had a delay of less than one hour. The sharp drop to the right shows the few flights with long delays. It should be mentioned that the delays do not refer exclusively to the actual course of the flight, but to the planned arrival. Delays in departure, e.g. due to weather or loading delays, lead directly to delays in arrival.

These two examples of illustrations show the advantages of a simple and fast extraction of information from the available data with the help of MATLAB.

In terms of fuel consumption, long flights are of interest, as a high proportion of fuel is required and transported as weight before consumption. This information can also be evaluated quickly. Figure 5 and 6 show the information on the distribution of block and flight times. Block time, as distinct from flight time, includes the time spent taxiing on the ground, before and after the flight. Evaluation with the help of boxplots of block and flight times show the relationship between these two parameters, however they are not listed here. The broad proportion of flights lasting more than five hours can be seen.

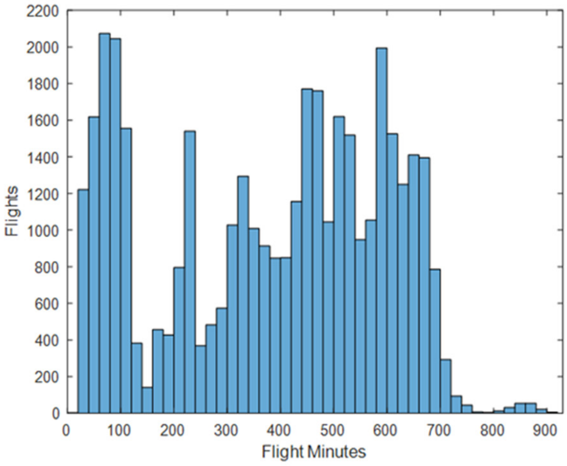

Figure 5: Flight Time

The evaluation of the flight times also shows a small but relevant number of flights with times between 800 and 900 minutes. These flights should be considered in more detail in the further development of the fuel consumption. Long flights, with high cargo and correspondingly high fuel content, offer the greatest opportunities for various parameters such as weather or flight route to have an influence.

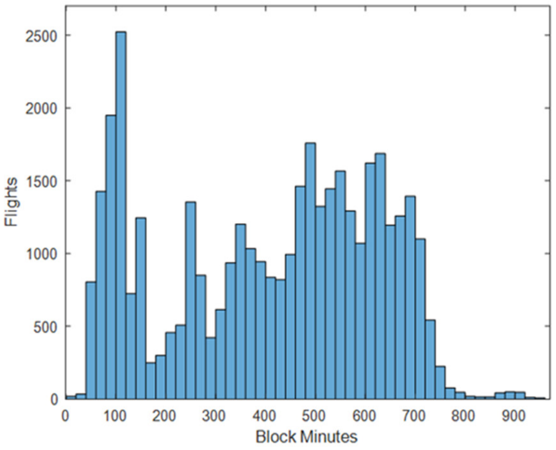

Figure 6: Block Time

The two peaks reflect the flights in the network. Short flights of 1 to 2 hours within Europe and medium to long haul flights worldwide.

Finally, information on the average load of the flights should be presented. As can be seen from Figure 7, the majority of flights were travelling with a load of between 60 and 100 tonnes, with an average of 70 tonnes. Some higher values than the maximum permissible loading, presumably incorrect values, were also found. This information may be relevant for the evaluation of routes without sufficient load. More interesting, however, are those flights that have a high load and possibly also a long flight time.

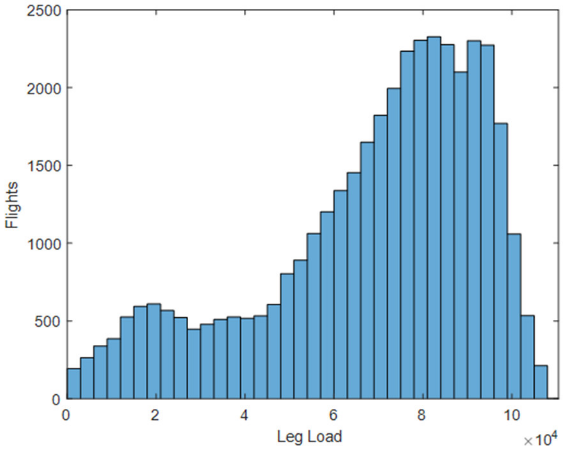

Figure 7: Leg Load

Further information, such as the city pairs flown and the aircraft's registration number, can be obtained from the above-mentioned report. However, these are not relevant for further fuel-related evaluation, in the first step.

Fuel Analyzer App References List Report

The Fuel Analyzer App References List Report contains information for 31 315 flights, period 1st march 2016 till end of December 2020. This reports is, amongst other things, fed by planning information and return information, send from the aircraft. It contains planned (p), actual (a) and corrected (c) information. Planned figures are self-explanatory, e. g. scheduled departure time, actual figures are true figures, like actual departure time. Actual figures describe the figures as sent by the aircraft. The report contains furthermore corrected figures. Corrected figures describe the difference between planned and feedback figures, based on the actual fuel decision and the payload of the flight. The Fuel Analyzer App References List comprises the data, which is used to feed the Fuel Analyzer App.

One of the safety performance indicators mentioned in the GM on Opinion 02/2020 is the number of landings with less than final reserve fuel (FRF). To obtain a statement about the planning and the progression of flights, a comparison of FRF and touch down fuel was done. Arriving at the destination, flights should have at least alternate fuel and final reserve fuel remaining on board or, in case of no alternate planning, FRF plus 15 minutes additional fuel. The final fuel reserve could be analysed in the Fuel Analyzer App References List report.

For 31 315 flights, the average FRF value was 2 954 kg, the mean, maximum, minimum and quantiles as shown in Figure 8. The maximum FRF value was recorded on the Shanghai - Frankfurt sector and the lowest on the Bahrain - Bangalore sector. Included here are 186 planned flights without alternate where an additional 15 minutes of fuel must be planned. These are included in the FRF of the reporting system of the air carrier, for technical reasons. Without these 186 flights, the average FRF would be 2 944 kg, only slightly below the overall average. These flights therefore have little influence and are only a small proportion of all flights. Figure 8 shows a corresponding boxplot evaluation.

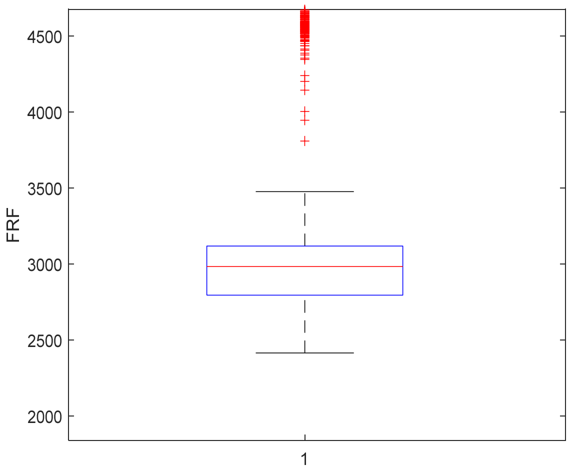

Figure 8: Final Reserve Fuel, with add. Fuel

The boxplot information on are:

- Median: 2 983
- Maximum: 5 031
- Minimum: 0
- Number recorded: 31 315
- Finite Outliers: 187
- NaN or Inf: 3 645
- 75th percentile: 3 118
- 25th percentile: 2 794
- Upper adjacent: 3 477
- Lower adjacent: 2 414

Interesting here is the flight with the entry "0 kg", which on closer inspection turned out to be a false entry. None of the analysed 31 315 flights landed below FRF fuel. The tightest buffer was around 300 kg of fuel at touch down above FRF for a flight which experienced extraordinary circumstances, more precisely the active eruption of a volcano, during the long-haul flight from China to America. Airspace was closed here. The affected flight was in close contact with the air traffic control centre throughout the entire flight and could thus make the decision to approach the destination airport.

The second plot, Figure 9, shows a histogram of the distribution of the FRF across the different flights . with a single pick at approx. 2 600 kg and the distribution around the mean of 2 954 kg.

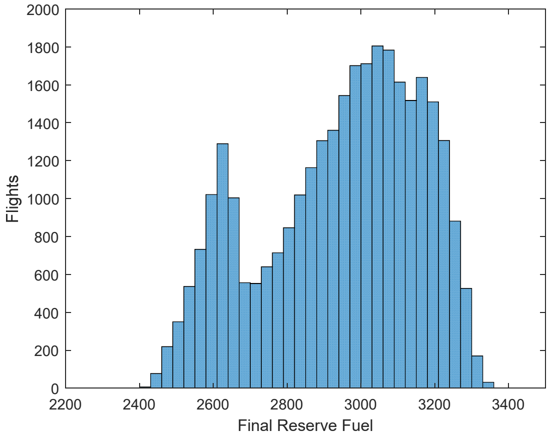

Figure 9: Final Reserve Fuel

CONCLUSION

The introduction of new regulations in the area of fuel requirements in the EU in 2022 enables air transport companies to optimise their planning and thus achieve savings in the area of fuel and emissions. At the same time, if a performance-based approach is chosen, proof of the equivalent level of safety must be provided before an approval can be granted. The evaluation of the necessary information, which is often available in large quantities, can be problematic. With the help of MATLAB, it is possible to quickly obtain clear representations of large and complex information out of the raw data. With the information obtained from the visualisations, proof of compliance with safety performance indicators can already be provided without any major pre-processing steps.

In the above section, only the first step of a statistical evaluation in this area was presented. However, this can already contribute to the demonstration of the safety performance indicators at this stage. Further evaluation steps can possibly provide even deeper and more comprehensive information which enable even better customised planning and also provide statistical information about specific routes or time periods. For this purpose, a more in-depth analysis of the data should be carried out with the help of MATLAB.

Further consideration of the interface to the reporting system is necessary, as there may be potential for further information and thus for optimisation. So far, only data from single point information, i. e. from planning or returned information, has been considered. No automatically transmitted data, which is transmitted at defined time intervals, was recorded. In addition, no evaluation of complex, time-stamped information took place, for which, for example, the use of the tall array would be necessary or possible.

AUTHOR BIOGRAPHIES

ANDREAS WALTER was born in Görlitz, Germany and started his career as a cadet in the German Air Force in 1997. As a young officer, he completed his studies in aerospace engineering at the University of the German Armed Forces in Munich. He then served as a technical officer in the German Air Force for seven years, dealing with all technical aspects of aviation. During this time, he studied business administration alongside his job at the FernUniversität in Hagen. After his military career, he moved to the German Civil Aviation Administration. Within the framework of a broad education, he got to know all the facets of aviation and eventually became an air operations inspector. He obtained the authorisation to fly various Airbus aircraft within the scope of commercial aviation, up to the authorisation as an instructor. His experience in supervisory work, his commercial and technical background provided the impetus and motivation to write a thesis in the field of fuel consumption. With the aim of combining his extensive and almost unique technical, organisational and operational experience, he is currently working on his PhD thesis at the Tor Vergata University of Rome and TH Wildau. His e-mail address is: walter.andreas@students.uniroma2.eu.

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