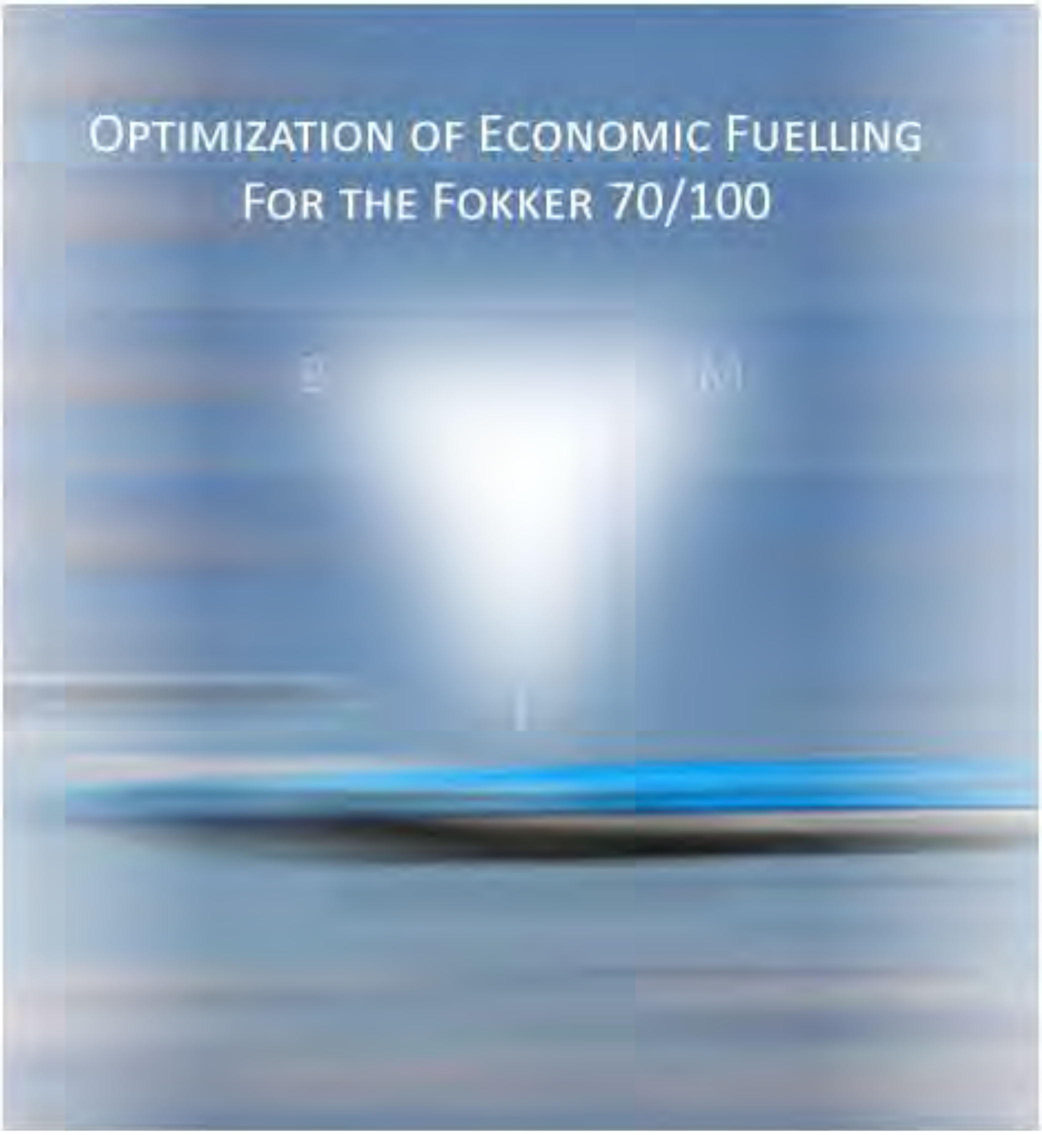

OPTIMIZATION OF ECONOMIC FUELLING FOR THE FOKKER 70/100

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Optimization of Economic Fuelling For The Fokker 70/100

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Preface

In order to complete the master course Business Mathematics and Informatics, students are expected to complete a thesis at a company. The subject of this thesis is the optimization of the economic fuelling for the Fokker 70/100 at KLM Cityhopper.

This is a public version of the final report. The following symbol denotes a block of removal because of confidentiality: ☒. One can contact Peter Derickx (Peter.Derickx@klm.com) for the complete report.

I would like to thank everybody who participated in this project and had a share in its successful completion. Many thanks to Wojtek Kowalczyk, Zoltan Szlavik, Ruud Stegers, Peter Derickx, Ewout Hilterman and Vincent van Valkenburg for giving their valuable input and guidance. A special thanks to Rene de Vogel and the KLC employees who helped me collect the data needed for the research. Last but certainly not least, I would like to thank my family and friends for their support.

Amsterdam, March 2010.

Abstract

The tumbling of the economy in 2008 and the aggressive emergence of low budget carriers forced many larger players in the aviation sector to try to further optimize their operational efficiency. Optimization of their operation is paramount for maintaining their success in such a competitive environment. The focus of this thesis is the optimization in the field of economic fuelling of KLM Cityhoppers (KLC) Fokker 70/100 fleet.

The current fuel policy oversimplifies the problem faced and therefore the aim of this research is to find an approach for the economic fuelling problem that optimizes the profit, by exploiting tankering as much as possible, and avoiding exposure to high deicing risk. We have seen that optimization of KLC's economic fuelling for the Fokker 70/100 is a complex problem. Solution to the problem involves both flight as well as weather parameters.

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Given the above input, model, and parameters one can estimate the amount of tankering fuel that needs to be taken by the plane to achieve maximum profit.

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Given these results, we recommend that KLC implements our new approach that optimizes the economic fuelling amount.

Contents

1 Introduction

Aviation, scheduled air transport in particular, plays an important role in providing us with a safe means of transportation to a variety of destinations. The tumbling of the economy in 2008 and the aggressive emergence of low budget carriers forced many larger players in the aviation sector to try to further optimize their operational efficiency. Optimization of their operation is paramount for maintaining their success in such a competitive environment.

The focus of this thesis is the optimization in the field of economic fuelling of KLM Cityhoppers (KLC) Fokker 70/100 fleet. Economic fuelling, or in other words *tankering*, is the process in which a plane is filled with fuel at its *base station* (in KLC's case Schiphol) for the flight to the destination, as well as with fuel for the flight back to the base station. This is done because fuel prices at the destination (*outstation*) are usually higher and, therefore, fuelling at an outstation is less attractive with respect to the costs. On the other hand, with tankering, a large amount of super cooled fuel remains in the wing tanks upon arrival at the destination airport. This increases the risk of ice forming on the wings upon landing significantly. When ice has formed on the wings, it is necessary to *deice*. This involves costs between $500 (€360) and $5.000 (€3.600) per deicing treatment, depending on outstation. At least as important are the delays that are caused by the deicing. A deicing treatment takes a significant amount of time and, therefore, when deicing is necessary, this causes a delay for the next flight. Unsatisfied customers and logistical issues, that translate into an amount of profit loss, are the result. So given the possible consequences of economic fuelling, the problem faced is to determine how much extra fuel to take for a maximum profit.

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With the shortcomings of the current model in mind, ***the aim of this research is to find an approach for the economic fuelling problem that optimizes the profit***, by exploiting tankering as much as possible, and avoiding exposure to high deicing risk.

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Optimization of the fuelling policy would lead to an increase of the profit in two ways. By using more parameters as indicators for the deicing risk, we can more precisely separate the risky from the less risky flights in terms of deicing probability. By doing so we can take more economic fuel for the less risky flights to increase tankering profit, and take less fuel for the risky flights to avoid the financial deicing risk. Furthermore, it is possible to find the optimal tinkering amount for a given flight by maximizing the margin between expected costs and profits. Through scenario analysis it is possible to look into the impact of the new model on the profit, using historical data.

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2 Background

This chapter provides the reader with useful background information related to fuel induced icing. The purpose of the background information is to help the reader gain an understanding of the operation within KLC, identify the factors that may influence the probability on fuel induced icing and to get a feeling of the size of the economical impact of deicing.

2.1 Fuel induced icing and its threats

Ice on the wings can cause risks regarding the flight safety. In this thesis we are especially interested in the ice forming on the wings that occurs after landing and is caused by the phenomena of fuel induced icing. We speak of fuel induced icing when freezing condensation has formed on a cold wing tank as a result of the cooling of the fuel during a high altitude flight[1] If the humidity in the air is at a certain level (due to e.g. drizzle or fog), it contains enough moisture to condense out on the wing, but not enough to raise the temperature of the wing surface quickly. After the condensation spreads over the wing to some extent, it eventually starts freezing there where the wing surface is more directly cooled by the cold remaining fuel. This usually happens a short period after landing. Wing icing in flight at high cruising altitudes is scarcely possible, because of the low water content of the air at such altitude.[2]

Fuel induced icing poses a number of threats. The first is that it causes aerodynamic difficulties. The wings of the Fokker 70/100, the plane type we focus on in this research, are designed in such a fashion that they create enough lift for take off, without any mechanical alterations of the structure of the wing. The margin at take-off is not increased by the use of slat (i.e alterations on the front of the wing) as with some other aircraft types. The wings and wing structure with which the airplane takes off are exactly the same as when flying at cruise altitude. A characteristic of these multi purpose wings is that they are super critical. A ‘supercritical wing’ is a commonly used term in aircraft design. This wing design reduces drag at high speeds (close to the speed of sound), and thereby increases fuel efficiency. The price of that is very low tolerance for disturbances of the airflow by for example ice formation on the wing[3]. For optimal lift it is absolutely necessary that the surface on the upper side of the wing remains clear of any unevenness that could disturb the airflow around the wing. A smooth wing surface results in a smooth

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[1] Flight International, 2 April 1988 [p. 36]
[2] Flight International, 2 April 1988 [p. 38]
[3] Comment on this thesis by Ruud Stegers, Captain Fokker 70/100.

airflow around the surface. Because of the form of the wing, air travels a longer distance over the upper side of the wing than below the wing. According to Bernoulli's principle an increase in the speed of the air occurs simultaneously with a decrease in air pressure. This means that the air above the wing has a low pressure relative to the air below the wing. This causes the desired lift upwards. Obviously, when ice forms on the upper wing surface this disturbs the airflow around the wing which reduces the pressure difference above and below the wing. This, in turn, reduces lift. In figures 2 and 3 the effect of icing on the wings on the lift is illustrated.

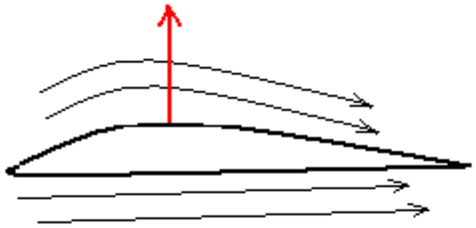

Figure 2: A smooth wing surface causes air above to move faster than below. This causes a certain lift up at a certain velocity.

Figure 3: Ice on the wings disturbs the airflow reduces the pressure difference above and below the wing. This causes the lift to be smaller at a certain velocity.

Contrary to the normal situation, an airplane cannot take off at normal take off velocity when ice has formed on the wings. This can result in a risk of overrunning the runway or losing the ability to stay in the air after take-off.

Another ice related threat comes from the risk of the so called ice ingestion. This is when ice, formed on the wings, gets loose during flight and reaches the jet engines that are situated on the tail of the Fokker 70/100. This could cause serious damage to the engines.

The threats discussed in this paragraph make airliners put great emphasis on the need of deicing in case ice forming has occurred.

2.2 The flight process

This paragraph outlines the different steps of the flight process. It is important to understand these steps to see how flight planning and flight realization are related to each other and what the possible deicing moments are, and, to have a clear picture of the events that precede these deicing moments.

Figure 1 shows the vertical flight profile for a flight, from Amsterdam to an outstation. An outstation is an airport other than Amsterdam. Underneath the profile, numbers depict the several phases of the flight. Every step is described individually below.

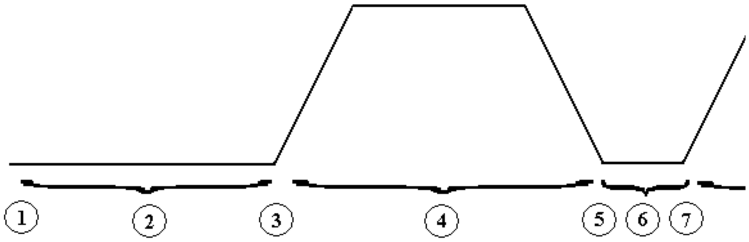

Figure 1: Vertical flight profile with corresponding steps in flight process.

1. ☒
2. This is the time period between creating the flight plan and actual departure to the destination. Somewhere within this time span, well before takeoff, the two designated pilots for the flight obtain their flight plan and walk through the given flight plan to discuss potential weather issues and approaches to deal with these. With updated weather information they can also decide to take (additional) tankering fuel even though the flight plan suggested not to tanker or to take only a small amount of tankering fuel. A problem, however, is that there are additional costs involved for recalling the fuel truck for, among other things, tankering. Sometimes, extra fuelling at this stage is not even an option because of time restrictions. That is why it is best to decide more accurately about tankering during composition of the flight planning. This will avoid the need to call back the fuel truck and reduce costs.
3. After some essential checks (e.g. engine performance, brakes, check whether total weight of load is within boundaries) the plane takes off for the flight to the destination.

4. This is the time period during which the flight from AMS to an outstation is realized. During the flight at high altitude the airplane is exposed to extremely cold conditions. This causes the fuel temperature to drop drastically. This drop will increase the possibility of fuel induced icing when the plane lands.
5. This is the moment of touch down at the outstation.
6. At the outstation there is a limited amount of time to prepare the airplane for the flight back to station AMS. At arrival at destination outstation an inspection of the plane is done to identify possible ice forming on the wing surfaces and other surfaces or to identify other matters that need special attention. If ice has formed, deicing needs to be done. This can be done by spraying a hot deicing mixture of fluids on the surface of the airplane. This melts the formed ice and prevents new ice forming for a specific amount of time (anti-icing). This is a costly procedure (see Section 2.5). The costs range between $500 (€360) and $5.000 (€3.597). Another way to get rid of the formed ice, is to fuel the wing tanks with fuel held at atmospheric temperature, which is relatively warm fuel. This increases the fuel temperature of the resulting fuel mixture, which causes the ice to eventually melt. Due to the generally short turn-around times (40 minutes) this generally is not an option: there is simply not enough time to melt the ice. If there is not enough fuel left for the flight back to AMS, refueling is anyhow needed. Alternatively, if the temperature at the outstation is not too low and time restrictions allow it, the pilots can decide to rely on the atmospheric temperature itself to melt the formed ice in time. This is not costly, but is only possible under specific conditions. If ice has formed, pilots usually resort to the expensive deicing fluids.

Form of deicing	**Restrictions**	**Costs**
Deicing treatment by use of deicing fluids.	None	High
Mix cold fuel with relatively warm fuel to increase temperature of wing tanks.	Atmospheric temperature has to be high enough and there has to be enough time to allow formed ice to melt (turn around-time).	Low
Use the heat from the atmosphere to melt the formed ice	Atmospheric temperature has to be high enough and there has to be enough time to allow formed ice to melt (turn around-time).	Low

Table 1: The possible ways to deice and their restrictions.

7. Again, the checks (e.g. engines performance, brakes, check whether total weight of load is within boundaries) before the flight back to AMS are performed. If deicing was necessary in step 6, the actual departure time for the flight back to AMS may differ from the planned departure time because of delay.

The answer to the question whether ice has formed or not depends not only on the conditions during the flight but also on the weather conditions upon arrival at destination. The weather conditions at flight planning can act as a predictor for the weather upon landing. We look more closely at the risk factors for fuel induced icing in the next subsection.

2.3 Risk factors for fuel induced icing

With a better understanding of what fuel induced icing is and what the flight process looks like, we can now outline the factors that are expected to have an influence on the probability on fuel induced icing and have corresponding data available. Multiple factors play a role as a possible cause, or part of the cause, of fuel induced icing. There are 3 different factors that affect the risk on fuel induced icing .

1. Fuel factor: Fuel temperature as well as the remaining fuel amount at the destination form an important factor for the risk on ice forming on the wing surface. The larger the amount of remaining fuel, the larger the wing surface in direct contact with the cold fuel. A large quantity of remaining super cooled[4] fuel in the wing tanks obviously increases the risk of ice forming on the wings. Furthermore, if the amount of remaining fuel is small, refuelling at the outstation will be necessary. This will cause the cold fuel to mix with relatively warm fuel. This increases the fuel temperature and reduces risks of fuel induced icing.
2. Meteorological factors:
    a. Temperature upon landing at the destination: If the temperatures are below zero, any formed ice will not melt on its own. This leads to the need for deicing. With temperatures well above zero, heat in the atmosphere may melt off any formed ice in a short time span.
    b. Temperature at cruise altitude: In general, the higher the altitude, the lower the temperature at that altitude . And the lower the temperature, the more and the faster the fuel in the wing tanks cools down.
    c. Humidity at destination: The humidity can be measured through the dew point. The dew point is the temperature to which a given parcel of air must be cooled, at constant barometric pressure, for water vapor to condense into water. This implies that if the dew point spread (the difference between dew point and temperature) is low, water in the air will condense into very small drops on the cold wings. These will in turn freeze when the temperature of the wing is below zero. For ice to form, the availability of water is a requirement. Condensed water on the wings increases the risk of ice forming on the wings.
    d. Weather type at destination: As opposed to dry weather, a weather type with precipitation like drizzle, rain or snow would stimulate ice forming on the wing surface and increase probability on fuel induced icing.
    e. Visibility at destination: Bad visibility indicates high humidity and an increased risk of ice forming on wings.
3. Flight factors:
    a. Flight duration: A large flight duration means that the fuel in the wing tanks is exposed to the extremely cold conditions at high altitude for a large duration. This increases the fuel induced icing risk.
    b. Flight altitude: The higher the cruise altitude is, the lower the temperature at that altitude.

It is important to notice that no single factor can predict the probability on fuel induced icing well, and to reach a good predictor it is necessary to use a combination of factors. It is the combination of factors that is decisive. For example, a temperature upon landing at an outstation of -10 degrees Celsius on itself does not increase the deicing probability if there is no moisture in the air to form ice.

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[4] By super cooled we mean that a substance has a temperature well below the freezing point of water.

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4 Data collection

In order to get the ☒ model to produce high quality probability estimations for deicing, we have to fit the model to real historical data. This historical data is not readily available in the form desired for this study, and therefore needs to be collected from different sources and preprocessed to serve our goal. The data needed will have to be in the form of a table in which a row represents an individual flight and the columns contain the relevant flight and weather attributes and information on whether a flight was deiced. In the context of our objective, we will need data of three different natures. The first piece of data contains specific flight information such as arrival and flight codes, departure times, flight altitudes, etc. The second piece of data contains deicing information. For every flight it is essential to know whether the flight is deiced or not. Furthermore, we are interested in the weather conditions at the outstation at the moment of planning for every flight that either resulted in deicing or not.
This chapter elaborates on the data collection and the data manipulations that shaped the data set for its eventual use in this research. Figure 7 provides an overview of the data gathering process.

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4.1 Scope of data and remarks

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We have to keep in mind that the data is biased due to the fact that there already is a fuel policy in use, meant to minimize deicing. See Section 2.3 *The current fuel policy* for more information on the current fuel policy.

The data manipulations done to create a useful complete data set, were executed in R. R is a programming language and software environment for statistical computing and graphics.[5] Though data manipulation is not R's core purpose, R is very appropriate for manipulating data.

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[5] Wikipedia (R programming language): last accessed 22nd of March 2010.

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4.4 The weather data

The third and final set of data we need for the final table is the weather data. If a flight is labeled with the deicing information, we need to know what weather conditions led to that label. We specifically need the weather conditions three hours before departure, because this is the moment flight planning is made taking the weather conditions of that moment into account.

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4.5 Joining the data parts

After obtaining the three parts of data described previously, the next step is to combine them into one large data set. First, the flight records are joined with the corresponding deicing information. This is a straightforward operation in which a well defined database join is made based upon the flight code and the departure date. The resulting joined data set is then joined with the weather data. This step is less straightforward, because for every flight the weather measurements three hours before departure must be identified and then linked to the flight record.

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But, as mentioned earlier, the maximum difference between moment of planning and time of measurement can be 15 minutes which is not expected to have a significant effect for further steps of the research.

It is important to note is that the departure times in the data warehouse are registered in Coordinated Universal Time (UTC) while the timestamps in the weather data are in local time. Therefore, in the search for the closest matching weather record for a certain flight, the local times need to be converted to UTC. Figure 8 shows four time zones, out of which three (0,+1,+2) are used in KLC outstations.

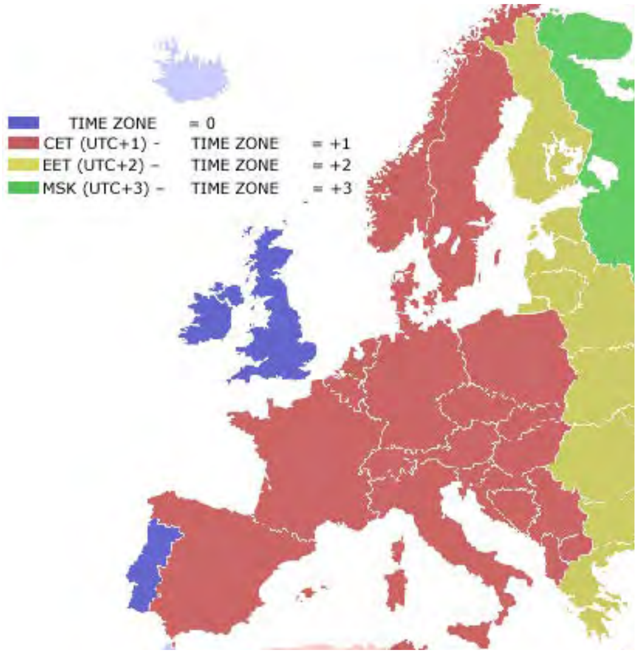

Figure 8: European time zones (western, central and eastern Europe).

The time conversions can be found in table 2 below.

	Look up time value in weather data corresponding with departure time (UTC) - 3	
	Summer	**Winter**
Eastern Europe	departure time (UTC) – 2	departure time (UTC) – 1
Central Europe	departure time (UTC) – 1	departure time (UTC) – 2
Western Europe	departure time (UTC)	departure time (UTC) – 3

Table 2: Time conversions UTC to local.

The three data parts, flight, deicing information and weather are now contained in one data set. The join steps mentioned, are performed in R (see appendix F) . The join with the weather data in which the nearest match of the weather measurements is linked to the flight records, regarding the weather station, date and time of the measurement, completes the data set, ☒.

5 Exploratory Data Analysis

Exploratory Data Analysis (EDA) is an approach for data analysis that employs a variety of techniques (mostly graphical) to maximize insight into a data set, uncover underlying structures and test some underlying assumptions. Therefore, the EDA also serves as an initial attribute selection step. We try to look at how we can dissect the data set in terms of the deicing cases and the cases in which there was no deicing. This is done by looking for answers to the question what the specific characteristics are of the deicing cases and those of the cases in which there was no deicing, respectively[6]. In essence, we look at the empirical distribution of the attributes like temperature, dew point spread, humidity and others. We do this per individual class (deiced flights and flights that were not deiced). These empirical distributions of the two classes are then compared to each other to uncover differences in characteristics and by that, uncover the ability to distinguish a class based on a certain attribute. The EDA is performed in R using the data that resulted from the data collection (Chapter 4). See Appendix G for the used R functions.

This chapter provides the reader with the EDA plots, tables and a description of the observations. Finally, we conclude the chapter with an overview of the findings from the EDA. The aim of the EDA is to identify attributes and, whenever possible, we finish a subsection by stating whether the investigated feature or combination will be considered as an attribute for our predictions

5.1 Overview per plane type

In this section we investigate the different plane types in the historical data to see whether the deiced cases are evenly distributed among the plane types.

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☒ flights with a night stop at an outstation resulted in deicing before the flight back to Amsterdam. Obviously, this is a higher ratio than that of flights without a night stop at an outstation. As stated before, this is probably not fuel induced icing, but icing caused by a long time exposure to cold weather conditions at the station. As these cases are not likely to be fuel induced icing cases, and they would contaminate our data set, these are not taken into account.

The Fokker 70 (F70) has a higher deicing percentage than the Fokker 100 (F100). The airplanes are physically almost the same and in the periods that fall within the scope, there were about as many F70's as F100's. This is probably because of the bias in destinations for both types of airplane. For popular destinations more will be sold, so a 100 seater, the Fokker 100, will be used on that route.

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[6] Engineering Statistics Handbook (http://www.itl.nist.gov/div898/handbook/eda/section1/eda11.htm), last accessed on 17th of February 2010.

5.2 Temperature at planning

Because ice forming is more likely under freezing conditions, temperature is an important indicator of the probability of ice forming on the wings.

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5.3 Dew point spread

The dew point is the temperature to which a given parcel of air must be cooled, at constant barometric pressure, for water vapor to condense into water. So, the dew point in itself does not contain enough information to say something about the amount of moisture in the atmosphere. It's the difference between atmosphere temperature and dew point (the so called dew point spread) that defines the humidity in the air and thus has a logical influence on the probability of ice forming.

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5.4 Relative humidity

Dew point and the relative humidity are related to each other. Relative humidity is the amount of moisture in the air compared to what the air can "hold" at that temperature. When the air can't "hold" all the moisture, then it condenses as dew. The greater the dew point spread, the less the amount of water in the air compared to how much it could hold.

5.5 Weather type

The weather type has a straightforward impact on the probability of ice forming. We expect that especially in situation with precipitation in the form of snow or light rain there is a real chance deicing will be needed.

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5.7 Flight duration

The flight duration has a relationship to ice forming in the sense that a longer flight duration involves a longer flight at high altitude, exposing the airplane and the fuel in the wing tanks for a longer period of time to extremely cold weather conditions, which inevitably increases the cooling of the fuel in the wing tanks.

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5.8 Flight planning top of climb

The top of climb tells us something about the altitude at which the cruise flight took place. The higher the altitude, the lower the temperature of the atmosphere, the more the fuel gets cooled. Since the actual altitude of a certain flight usually fluctuates, the top of climb from the flight plan is an indication of actual flight altitude.

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Experts informed us that there is a correlation between flight duration and flight altitude. The further the destination (the longer the flight duration), the higher the flight altitude. Furthermore there are some altitudes specifically reserved for inbound flights and other altitudes specifically reserved for outbound flights. This explains the humps we see in Figure 14.

5.9 Remaining fuel upon landing

We expect a relationship between the amount of remaining fuel at the outstation and the risk of ice forming on the wing surface. This is because the remaining fuel after a flight at high altitude has a very low temperature. The substantial amount of cold mass in the wing tanks then cools the wing surface, making it able for any moisture in the air to turn into an ice layer on the wing surface. The remaining fuel upon landing is calculated as a difference: it is the actual departure fuel amount minus the actual burned fuel amount. ☒

5.10 Months overview

In this subsection we look at how the different cases are distributed over the months of the past two winter periods.

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5.11 Weather development

In this subsection we look at the average weather development over the day. The early mornings are usually colder than the noons. The temperature drops again as the evening approaches. But how steep are these rise and drop in temperature? And what are the effects on the humidity? For the following graphs, data from all outstation are taken into account.

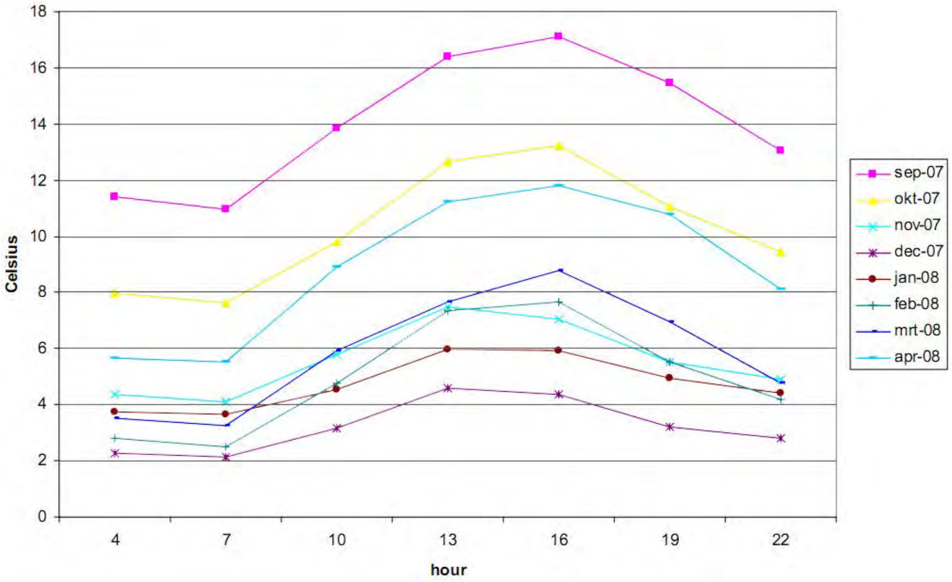

Figure 16: Temperature development over the hours of the day (averages of winter 2007-2008).

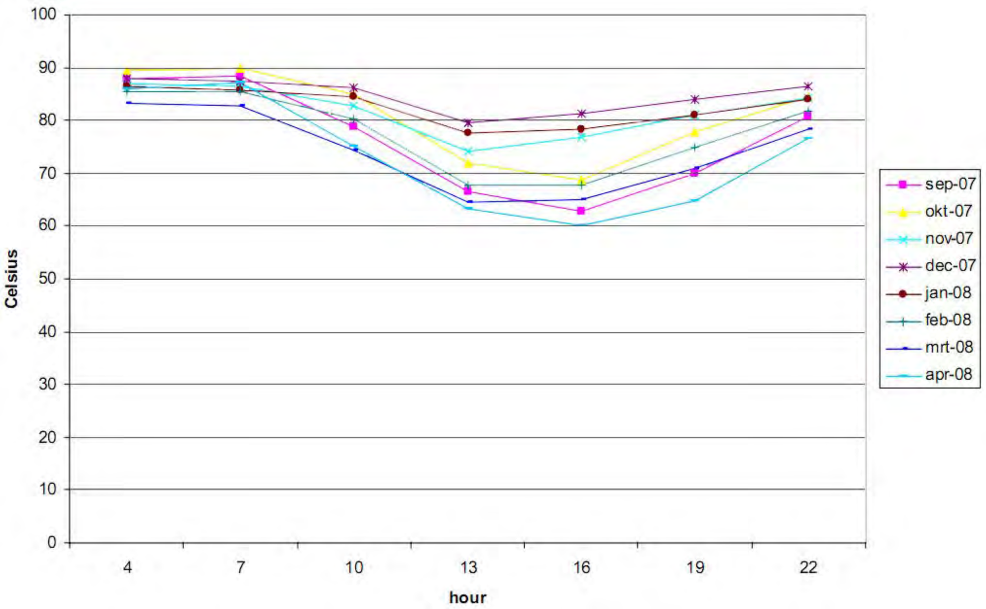

Figure 17: Humidity development over the hours of the day (averages of winter 2007-2008).

Figures 16 and 17 show that in the time span between flight planning and actual arrival of about 5 hours the temperature can change substantially. Flights that are planned around 6:00 AM can on average encounter a temperature rise of about 5 degrees Celsius on arrival. Flights planned around 4:00 PM may on average encounter a temperature drop at arrival of about 4 degrees Celsius. We see that these fluctuations are less in the colder months December, January and February. The humidity on average drops as the temperature rises over the day and vice versa. For instance in April, a flight planned on 10:00 AM may on average encounter a relative humidity level 20% lower than at time of planning. This points out that the arrival time of a flight will probably be a helpful attribute for the model to predict the deicing probability, since it contains information about how the temperature and humidity levels will develop. This is essential information for an accurate prediction.

We can also compare the temperature development over the day on an outstation in the northern part of Europe to the temperature development over the day on an outstation in the southern part of Europe.

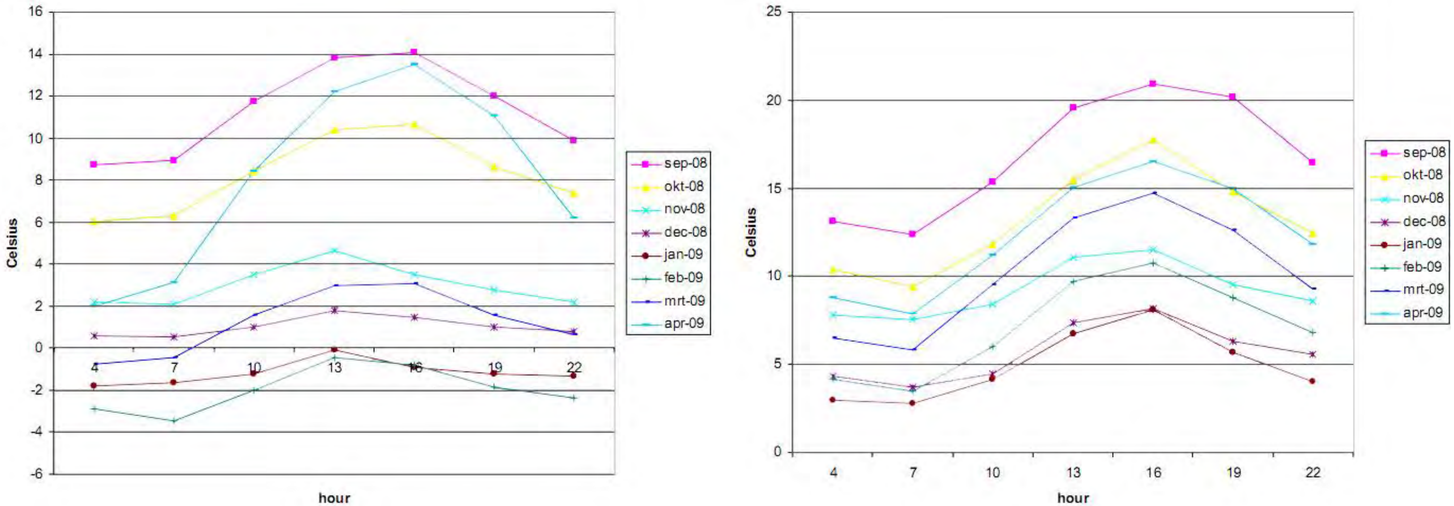

Figure 18: (A) Average temperature development over the day in Linkoping (2008-2009). (B) Average temperature development over the day in Bordeaux (2008-2009).

From figures 18A and 18B it is clear that the temperature in the northern region of Europe is structurally lower. Also, in the colder region the temperatures in the month April seem to fluctuate more over the day. So, like the time of the day, the location of the outstation will help the model make a more accurate prediction of the temperature upon arrival at the outstation, since it contains implicit information on what to expect of the weather in the near future.

5.12 EDA findings

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In this chapter we have described the EDA and identified possibly important factors that help predict deicing. In the next chapter we take these attributes and build a model to estimate the probability of deicing.

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7 Demonstrative Example

In this chapter we provide a demonstrative example of the implementation of the economic fuelling approach ☒. The purpose of the demonstration is to help explain the solution to the optimization problem to KLC and it might form the basis of economic fuelling recommendation system. The demonstration can be found in the Excel sheet *Optimizationsheet.xls*. Interested readers can contact Peter Derickx (Manager Fuel and Weight Savings at KLC) at Peter.Derickx@klm.com in order to obtain the file with the demonstrative example. For the demonstration we use actual historical data of flight 1173 to Trondheim. It shows the steps involved for the decision making about the economic fuelling amount.

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We have created an easy to use Excel sheet that calculates the estimated best tankering amount. ☒
Flight and weather information concerning the flight are used as input for the model. ☒

8 Conclusion

We have seen that optimization of KLC's economic fuelling for the Fokker 70/100 is a complex problem. Solution to the problem involves both flight as well as weather parameters. The current fuel policy oversimplifies the problem by taking too few information into account and thus does not provide us with the optimal fuelling policy.

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☒ we recommend that KLC implements our new approach that optimizes the economic fuelling amount.

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9 Further research

Given the scope and the findings of our research, there are a number of topics that could be subject of future research:

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- This thesis focused on the economic fuelling problem for the Fokker 70/100. It would be interesting to do a similar research for other plane types that are vulnerable to fuel induced icing.

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11 Appendix

Appendices A to C and E to H can be found in the Digital Appendix attached to the hard copied report. They can also be obtained by contacting Peter Derickx (Peter.Derickx@klm.com).

(Appendix D)