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Risk analysis of the EASA minimum fuel requirements considering the ACARE-defined safety target

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ABSTRACT

We present the results of flight simulator experiments (60 runs) with randomly selected airline pilots under realistic operational conditions and discuss them in light of current fuel regulations and potential fuel starvation. The experiments were conducted to assess flight crew performance in handling complex technical malfunctions including decision-making in fourth-generation jet aircraft. Our analysis shows that the current fuel requirements of the European Aviation Safety Agency (EASA) are not sufficient to guarantee the safety target of the Advisory Council for Aviation Research and Innovation in Europe (ACARE), which is less than one accident in 10 million flights. To comply with this safety target, we recommend increasing the Final Reserve Fuel from 30 min to 45 min for jet aircraft. The minimum dispatched fuel upon landing should be at least 1 h.

1. Introduction

1.1. Background

On behalf of the European Commission, the Advisory Council for Aviation Research and Innovation in Europe (ACARE) recommends various research activities including a strategic path towards increased flight safety (ACARE, 2011; 2012). ACARE aims to keep the average number of accidents in Europe below a maximum of 20 per year, taking into account the growth in air transport until the year 2050 (ACARE, 2002). ACARE also defines a safety target for airline passenger transport, a so-called Acceptable Level of Safety Performance (ALoSP), such that “the European air transport system should have less than one accident [as defined by ICAO] per ten million commercial aircraft flights”, which translates into a target accident probability for a single flight of $p_{target} = 1 \cdot 10^{-7}$ (ACARE, 2011). $P(Accident)$ denotes the accident probability for an average single flight and it should be:

$$P(Accident) \le p_{target} = 1 \cdot 10^{-7} \quad (1)$$

Given the current European accident rate of 1.5 accidents per 1 million flights (IATA, 2016), which corresponds to $P(Accident) = 1.5 \cdot 10^{-6}$, this ALoSP requires a reduction in the accident rate of approx. 90%. In comparison, the global accident rate was 1.81 accidents per 1 million flights in 2015, i.e. $P(Accident) = 1.8 \cdot 10^{-6}$ (IATA, 2016). Therefore, improvements and mitigation strategies, so-called corrective actions, are necessary and must be implemented to achieve a significant reduction in the accident rate. The objective of this paper is to quantify the impact of a change in the current fuel regulations for jet aircraft as a major corrective action.

To identify suitable and effective corrective actions, one has to identify the causes of an accident first and then quantify their contribution and dependencies. Ale et al. (2005) developed a model of the whole air transport system, termed Causal Model for Air

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Transport Safety (CATS), which includes the causal chain of accident sequences (Ale et al., 2005, 2009; CATS Consortium, 2008). In total, the model represents 35 accident categories that are described by event-sequence diagrams as well as fault and decision-trees. The CATS model is integrated into a Bayesian belief network that allows for the quantification of the overall level of safety and accounting for dependencies between causal factors.

In Drees and Holzapfel (2011), Drees et al. (2014), Wang et al. (2014), and Zwirglmaier et al. (2014), Drees (2017), a physics-based approach is presented in which accidents are modeled by taking the known physical relationships between factors that contribute to an accident into account. Similar to the CATS approach, sensitivities are quantified that describe the individual contribution of each factor to the accident probability.

One factor that relates to aviation safety is the amount of fuel. Due to the large proportion of fuel costs on the total airline costs, airlines are interested in finding the optimal/minimum amount of fuel for their operation. Ayra et al. (2014) present a Bayesian decision model to assess the optimal amount of fuel to be able to cope with holdings at the destination airport and to avoid unnecessary diversions due to fuel. They develop a decision tree that is fed with operational data from a major airline. The aim of the model is to support airlines in reducing their operational (fuel) costs by adapting the amount of fuel for holdings due to air traffic. The model does not account for the reduction in safety due to reduced fuel reserves.

Fuel consumption models are also available for the taxi phase (Nikoleris et al., 2011; Khadilkar and Balakrishnan, 2012). For example, Khadilkar and Balakrishnan present a regression model to quantify the amount of fuel during the taxi-out phase. Here, the model parameters are based on flight operation data from various aircraft types, such as the Airbus A320 or the A340.

In Wang, Drees & Holzapfel (2016), a method for quantifying the probability of fuel starvation caused by hub closure is presented. Here, an air traffic scenario model is described in which a hub airport closes and the approaching aircraft have to divert to a smaller airport nearby, which may not have the capacity to cope with all aircraft simultaneously. Therefore, aircraft may have to fly multiple holding patterns, and some aircraft may have to use their reserve fuel.

1.2. Current fuel regulations

The minimum fuel quantities required for passenger transportation in jet aircraft are defined by the International Civil Aviation Organization (ICAO) and are adopted by the European Aviation Safety Agency (EASA). They comprise the following components (ICAO, 2010):

- *Taxi Fuel* (the amount of fuel consumed on ground before take-off)
- *Trip Fuel* (fuel from departure to destination airport).
- *Contingency Fuel* (additional fuel for an unexpected fuel consumption)
- *Alternate Fuel* (fuel for the flight to an alternate airport)
- *Final Reserve Fuel* (minimum fuel upon landing)
- *Extra Fuel* (additional fuel at the pilot's discretion to cover delays or re-routings)

Fuel values are typically expressed in minutes of flight time. For jet aircraft, the *Final Reserve Fuel* should be sufficient for 30 min of flight time at 1,500 ft above the airport elevation at holding speed (ICAO, 2010). One has to keep in mind that these fuel regulations were defined when jet aircraft came into service more than 50 years ago, many of which have remained unchanged. Moreover, technical failures were not taken into account (EASA, 2016b; ICAO, 2010). Given the relatively low complexity of first and second[2] generation jet aircraft compared to today's aircraft[3], ensuring that additional time is available to handle a technical problem was considered less important. At that point in time (50 years ago), the complexity levels of abnormal or emergency procedures were relatively small. Also, the total number of flights only amounted to 5% of today's traffic (ICAO, 2016a). Therefore, severe traffic congestion at airports was nonexistent. The question now arises as to whether the requirement on *Final Reserve Fuel* is still up to date, or whether the complexity and length of abnormal procedures, the traffic volume and today's safety targets requires a modification.

EASA's fueling policy was modified in 2012 (EASA, 2012). At destination airports where more than one suitable runway is available and if the weather fulfills certain requirements regarding cloud base and visibility, *Alternate Fuel* can be substituted by an additional 15 min of fuel according to the new regulations CAT.OP.MPA.150 (b) (EASA, 2016a). Those 15 min of additional flight time can be used to cover possible unexpected delays, ensuring a landing with at least 30 min of *Final Reserve Fuel*.

2. ICAO safety management

The Safety Management Manual published by the ICAO requires airlines to identify hazards and unsafe conditions, so-called emerging risks, that have not yet caused an incident or accident (ICAO, 2013a; 2013b). Emerging risks should be reviewed and, if necessary, corrective actions have to be defined to take control of these emerging risks (ICAO, 2013b). This is achieved by performing quantitative risk assessments, including studies and experiments (ICAO, 2013b). The risk assessments must demonstrate that a proposed change in the aviation system does not increase the probability of an accident.

2.1. Safety requirements

The event 'accident' can be broken down into n subtypes AT_1, AT_2, …, AT_n, e.g., *runway excursion* or *loss of control in flight*. The overall probability of an accident $P(Accident)$ is the probability that at least one of the n accident types occurs:

$$P(Accident) = P(AT_1 \cup AT_2 \cup \ldots \cup AT_n) \quad (2)$$

An upper bound to $P(Accident)$ is the sum of the probabilities of the different accident types $P(AT_i)$. Because some accident types are correlated, the actual value of $P(Accident)$ will be lower; nevertheless, due to the overall very small probability of an accident, the approximation error when using the upper bound will be typically small. Hence, to comply with the ALoSP (Eq. (1)), the sum of probabilities of all different accident types $P(AT_i)$ has to be roughly equal to or less than the safety target of $p_{target} = 10^{-7}$ per flight. In line with the certification standards of the European Aviation Safety Agency (EASA) for large aircraft (EASA, 2007), we consider $n = 100$ (failure) conditions that could potentially be catastrophic and result in an accident. The overall ALoSP of $p_{target} = 10^{-7}$ can thus only be met if the average probability of individual accident types is in the order of $10^{-7}/_n = 10^{-9}$ per flight. It is not necessarily optimal or desirable to require the same safety level for all accident types, but we shall assume here that it is safe to state that the safety requirement for an individual accident type AT_i must be at *least* 10^{-8} per flight in order to meet the overall ALoSP. This means,

[2] E.g. Airbus A300, Boeing B737–100/200 (Airbus, 2016b).

[3] E.g. Airbus A320 Family, Boeing 777, Embraer E-Series (Airbus, 2016b).

however, that other accident types must have a safety requirement of less than 10^{-9} in order to meet the overall ALoSP of $P(Accident) < 1\cdot10^{-7}$.

We focus on the accident type ‘complex aircraft system failure’, $AT_{Complex\ Failure}$. During a complex failure event, pilots are confronted with demanding and time-consuming technical failures, such as double failures or failures that increase the fuel flow, and abnormal procedures that include instructions and checklists to handle those technical failures.

To obtain the probability of an accident caused by a complex failure $P(AT_{Complex\ Failure})$, one has to consider the probability of the event, $P(Complex\ Failure)$, jointly with the conditional probability that the crew is *not* able to handle the complex failure event, $P(Crew\ Failure|Complex\ Failure)$:

$$P\left(AT_{Complex\ Failure}\right) = P(Crew\ Failure|Complex\ Failure) \cdot P(Complex\ Failure) \tag{3}$$

2.2. Probability of a complex failure

To estimate the probability of a complex failure, we looked into a ten-year period (1997–2006) within a major European airline and found that three complex aircraft system failures occurred: the first event was a combination of a hydraulic failure with multiple tire bursts and a normal brake system failure on an Airbus A340 (BFU, 1999). The second event was a combination of a hydraulic failure with a non-retractable gear, including a diversion due to an unexpected deterioration of weather conditions on a MD11. During this event, the landing was completed at the alternate airport with less than 15 min of fuel remaining (Safety Department, 2002). The third event was caused by a ruptured bleed duct, which melted the insulation of a bundle of electrical cables in a Boeing 747–400. This caused a significant number of short circuits and triggered more than 30 system messages (LFT, 2007). In all of those complex aircraft system failure events, more than 30 min were required to handle the situation.

During that ten-year period, the airline conducted 5,634,695 flights, which allows us to estimate the occurrence probability of a complex failure incident *per flight* as:

$$P(Complex\ Failure) \approx \frac{n_{\ Failure}}{n_{Flights}} \approx \frac{3}{5,634,695} = 5.32\cdot10^{-7} \tag{4}$$

Given the small sample size, one should consider the statistical uncertainty associated with this estimate. The number of k complex failure occurrences in a fixed time period follows a Poisson distribution. A Bayesian analysis with a non-informative gamma prior (Gelman et al., 2014; Straub, 2015) results in a 90% credible interval for $P(Complex\ Failure)$ of $[1.5\cdot10^{-7}; 1.1\cdot10^{-6}]$

Complex failures are mainly relevant during the final approach of a flight (critical phase), when studying the effect of the *Final Reserve Fuel* on the accident probability. We take this phase as the last 15 min of the flight and let $r_{approach}$ denote its share of the total flight time. Under the assumption that complex failures are equally likely to occur during all phases of the flight, the probability $P(Complex\ failure\ during\ approach)$ is calculated as:

$$P(Complex\ failure\ during\ approach) = P(Complex\ failure) \cdot r_{approach} \tag{5}$$

The average time share spent in the critical phase is $r_{approach,short} = 17.9\,\%$ for short-haul flights (based on an average flight duration of 84 min) and $r_{approach,long} = 4.8\,\%$ for a long-haul flight (average flight time equals 312 min). The average flight durations are based on *all* flights within EASA's member states (short-haul) and to/from EASA's member states (long-haul) from 2015 (EASA, 2016b).

The average $r_{approach}$ is computed by combining values for short and long-haul flights by weighting them according to their respective proportion. In EASA's member states, 82.6% of the flights are short-haul flights and 17.4% long-haul flights (EASA, 2016b). This results in the following percentage of flight time spent in the critical phase of the last 15 min:

$$r_{approach} = 82.6\%\cdot17.9\% + 17.4\%\cdot4.8\% = 15.6\% \tag{6}$$

Inserting the values of Eq. (6) and Eq. (4) into Eq. (5) results in:

$$P(Complex\ failure\ during\ approach) \approx 5.32\cdot10^{-7} \cdot 15.6\% = 8.3\cdot10^{-8} \tag{7}$$

Complex failures are more likely to occur during the departure and approach phase, during which pilots interact with more aircraft systems than during cruise flight. For example, moving the landing gear and flaps are the most demanding events for the hydraulic system. To a certain extent this is also reflected in current accident statistics, in which the number of aircraft malfunctions contributing to accidents increases compared to other flight phases, e.g. cruise (IATA, 2014), and is also confirmed by expert judgement (Ahmadi et al., 2010). Therefore, Eq. (7) likely underestimates the probability of a complex failure during approach. Considering all uncertainties and necessary assumptions, we conclude that a credible interval for $P(Complex\ failure\ during\ approach)$ computed based on Eq. (5) provides a reasonable description, even if it might slightly underestimate the true probability. The resulting 90% credible interval is $[2.3\cdot10^{-8}, 1.7\cdot10^{-7}]$.

As airlines have a limited influence on the occurrence probability of a complex failure, we assume that $P(Complex\ failure\ during\ approach)$ is not affected by operations. Although the data on complex system failures is from 1996 to 2006, they are still representative for today's aircraft, as the relevant conditions have not changed significantly. Therefore, complex failure events occur still today on aircraft types that are operated by legacy and low-cost carriers, e.g. (BFU, 2015). Only a few of these incidents reach the public's attention, one example being the Qantas flight QF32 incident in which more than 50 warnings were triggered after an uncontained engine failure (ATSB, 2013). This incident also highlights the complexity of the system design in the latest generation of jet aircraft, which can foster complex failure events.

3. Simulator experiments

To assess the probability of a complex failure leading to an accident, $P(Crew\ Failure|Complex\ Failure)$, one must understand how cockpit crews actually handle complex technical problems in modern jet aircraft under *realistic* environmental conditions. To answer this question, simulator experiments (60 simulation runs) were conducted in 2014. Some findings of these experiments have already been reported (Gontar et al., 2014; Gontar and Hoermann, 2014, 2016; Gontar and Mulligan, 2015; Haslbeck and Hoermann, 2016; SaMSys Consortium, 2016; Schubert, 2015).

3.1. Participants and scenario

In total, 60 randomly selected crews, which included 120 fully qualified and type-rated airline pilots, were scheduled for experiments on Airbus A320 and A340-600 full-flight level D simulators. The simulator flights were scheduled as part of normal flight duties (fulfilling all duty time limitations and entailing normal payment for the time spent in the experiment). Participants scheduled for the simulator experiment were replaced by standby crews if they became sick or did not show up for the simulator experiment.

Two different airports were chosen: The A320 crews were to fly into Nice Cote d'Azur Airport (NCE), France on an approach to runway 22R, specifically a very high frequency (VHF) omnidirectional radio range (VOR) approach. A340-600 pilots were to fly into John F. Kennedy Airport (JFK), USA on a Canarsi VOR approach to runway 13R. The technical failures in the simulator scenario were the same for both the Airbus A320 and the A340. The experiments started on the final, non-precision approach about 5 min before the planned landing. The air traffic control (ATC) environment was as realistic as possible. Recordings of actual air traffic controllers of both Nice and New York could be heard; frequency congestion and eventual miscommunication had to be covered. At the start of the scenario, around 60 min of remaining flight time were available. Shortly after *flight freeze* was removed in the simulator, the landing gear had to be lowered (normal flight sequence). The malfunction started with a fluid leak in the green hydraulic system during gear extension. Due to the hydraulic failure, the landing gear extended only partially and could not be retracted further. The nose gear was in an intermediate position and not locked down. The partially extended landing gear caused an increase in fuel flow due to additional aerodynamic drag, reducing the remaining flight time to less than 40 min. The pilots had to fly a missed approach procedure. The abnormal procedures for the green hydraulic loss had to be carried out after the go-around, Electronic Centralized Aircraft Monitor (ECAM) actions and status together with the gravity or alternate gear extension. In addition, the in-flight landing distance computation procedure had to be applied.

In both scenarios (NCE and JFK), weather was not a demanding factor, as there were no low clouds. Visibility was good. Due to light winds coming from the south at only 10 knots, all runways and all landing directions could be chosen for approach. Another malfunction occurred after all the required procedures were completed and while intercepting the selected approach. A sluggishly operating (leading edge) flap segment triggered the activation of the wing-tip brake. Again, ECAM actions and the in-flight landing distance computation procedure had to be performed.

3.2. Simulator results

Figs. 1 and 2 show the tracks and altitudes in each scenario. Both figures suggest that although the scenario was the same for each crew, there is a high variability in how the crews actually handled the complex scenario with the cooperation of ATC.

Fig. 3 shows the times $t_{Complex\ Failure}$ of both scenarios (A320 and A340), corresponding to the time taken by the crews to handle the complex failure, including the average time, standard deviation, and the minimum and maximum time.

Regarding crew performance, the experiments showed that the increasing time pressure and additional workload created by the realistic communication with ATC significantly increased the error rate compared to normal simulator training (line proficiency checks) (SaMSys Consortium, 2016).

3.3. Probability of a crew failure given a complex failure

In this section, we use the measured times $t_{Complex\ Failure}$ from both flight simulator scenarios (Fig. 3) to derive $P(Crew\ Failure|Complex\ Failure)$. To obtain a probability from the time measurements, we compare $t_{Complex\ Failure}$ with the available flight time due to the quantity of *Final Reserve Fuel*. Specifically, we compare the available amount of fuel $m_{Fuel,\ Available}$ with the required amount $m_{Fuel,\ Required}$, which depends on $t_{Complex\ Failure}$:

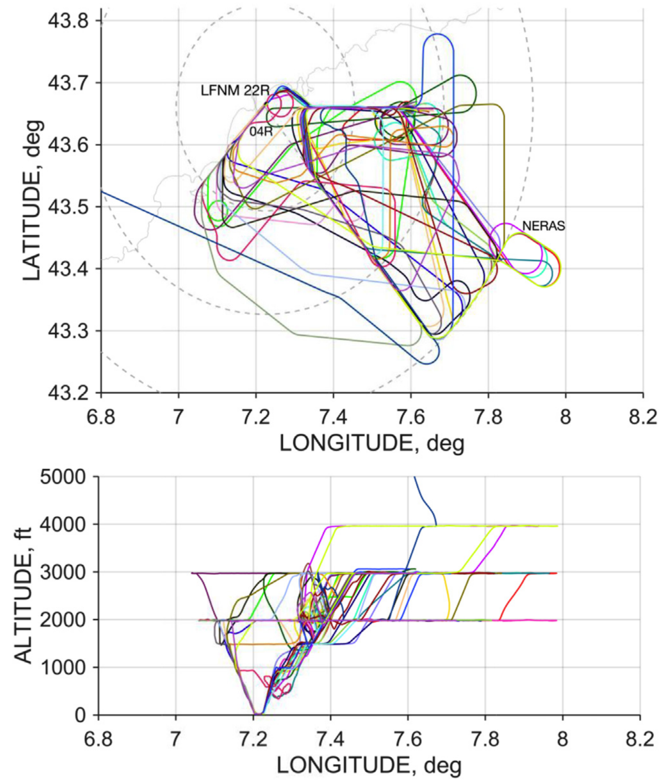

Fig. 1. Flight tracks in the NCE scenario according to Schubert (2015).

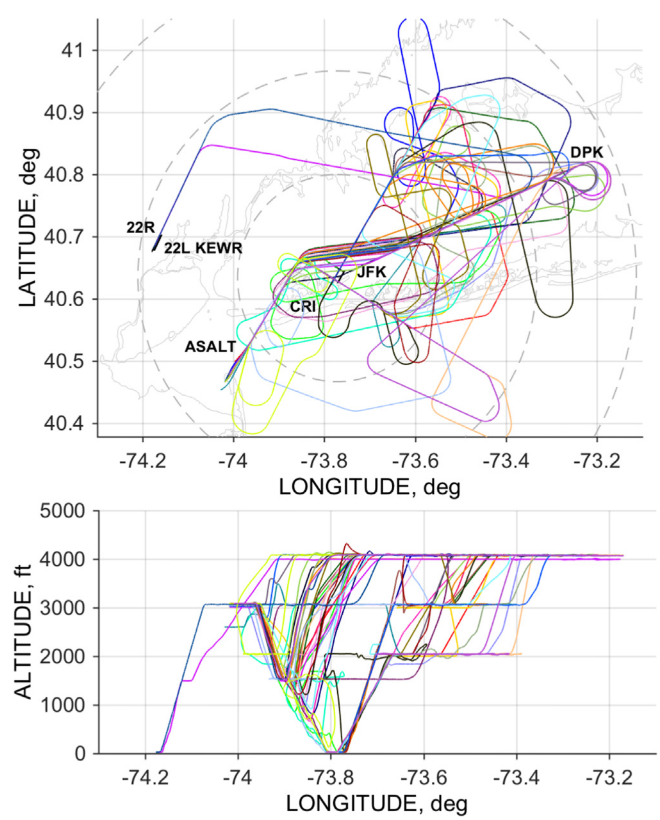

Fig. 2. Flight tracks in the JFK scenario according to Schubert (2015).

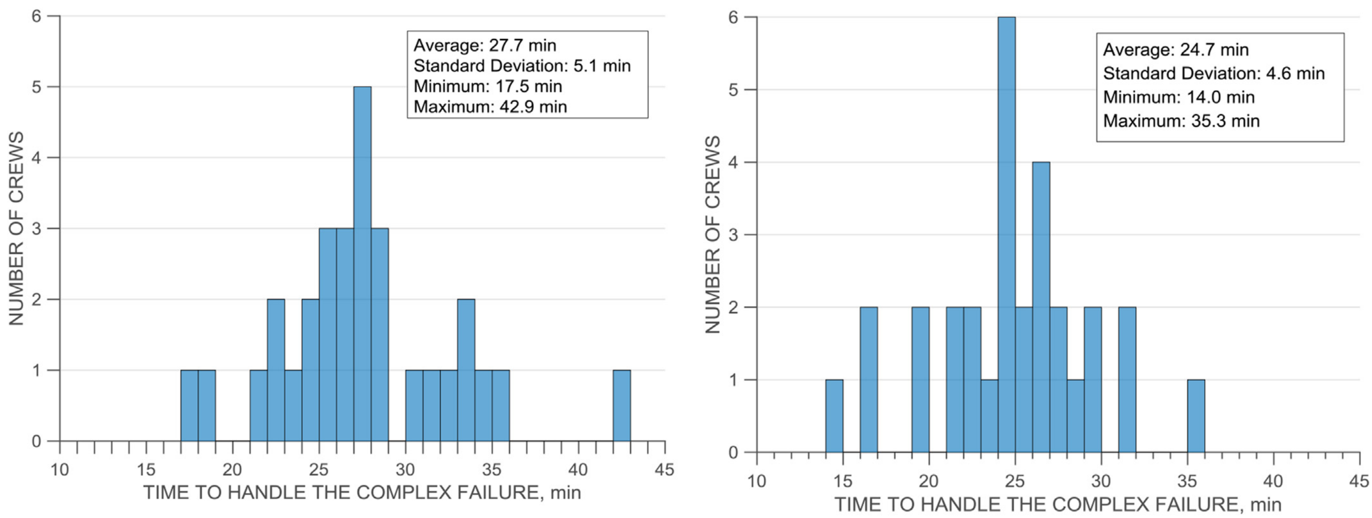

Fig. 3. Histograms of the time to handle the complex failure (NCE left, JFK right).

$$\Delta m_{Fuel} = m_{Fuel,\ Available} - m_{Fuel,\ Required} \quad (8)$$

This allows us to determine whether or not fuel starvation will occur:

$$\Delta m_{Fuel} \begin{cases} \leq 0 & Fuel\ Starvation \\ > 0 & No\ Fuel\ Starvation \end{cases} \quad (9)$$

In the following, we perform this comparison (Eq. (9)) for a time interval of 0–60 min, in which we calculate $m_{Fuel,\ Available}$ as follows, assuming a normal fuel flow $\dot{m}_{FuelFlow,normal}$:

$$m_{Fuel,\ Available} = t_{Available\ Flight\ Time} \cdot \dot{m}_{FuelFlow,normal}$$
$$t_{Available\ Flight\ Time} \in [0; 60] \quad (10)$$

Then, we calculate the amount of fuel $m_{Fuel\ Required}$ required to handle a failure scenario assuming a given fuel flow $\dot{m}_{FuelFlow}$ using $t_{Complex\ Failure}$:

$$m_{Fuel\ Required} = t_{Complex\ Failure} \cdot \dot{m}_{FuelFlow} \quad (11)$$

In the simulator data, we observed that the partially extended landing gear increased the fuel flow by approximately 40%. Therefore, we distinguish between two types of fuel flow: normal fuel flow $\dot{m}_{FuelFlow,normal}$ and increased fuel flow $\dot{m}_{FuelFlow,increased}$, where

$$\dot{m}_{FuelFlow,increased} = \dot{m}_{FuelFlow,normal} \cdot 1.4 \quad (12)$$

In the following, we combine the measured times $t_{Complex\ Failure}$ from both scenarios (A320-NCE and A340-JFK). Based on Eq. (8-12) and the aggregated times $t_{Complex\ Failure}$, we can calculate $P(Crew\ Failure|Complex\ Failure)$. Here, we evaluate the measured $t_{Complex\ Failure}$ under three scenarios (cases) to cover a wide range of possible failure conditions, whereas *Case 2* corresponds to the flight simulator scenario:

- **Case 1**: Complex double failure, e.g., two abnormal procedures without any gear problems, with *normal* fuel flow $\dot{m}_{FuelFlow,normal}$
- **Case 2**: Complex double failure, e.g., two abnormal procedures and partially extended landing gear, with *increased* fuel flow $\dot{m}_{FuelFlow,increased}$
- **Case 3**: Single failure, e.g., loss of the green hydraulic system and partially extended landing gear, with *increased* fuel flow $\dot{m}_{FuelFlow,increased}$

Fig. 4 shows the number of crews that would have required more than 30 min to handle the technical failure (i.e. potential fuel starvation) in *Case 1* as a function of the available flight time. Specifically, the x-axis shows the flight time $t_{Available\ Flight\ Time}$ available to the pilots to handle the complex, double-failure scenario. The left y-axis shows the number of crews that would have run out of time for a specific remaining flight time upon landing, which corresponds to $P(Crew\ Failure|Complex\ Failure)$. For example, if the remaining fuel lasts only for $t_{Available\ Flight\ Time} = 14\ min$, all crews except for one, which was the fastest crew at 14 min (Fig. 3, right), would run out of fuel. As this figure shows (Fig. 4), the higher the available flight time in terms of fuel, the higher the number of crews able to handle the failure scenario and the smaller the number of fuel starvations. The right y-axis shows the corresponding probability as a percentage.

With a remaining period of 30 min, as specified by the current fuel regulations, 18% of the crews (see right y-axis) within an error interval of [10%; 40%] would *not* have had enough time to handle the problem. We consider an error interval of 3 min, indicated by

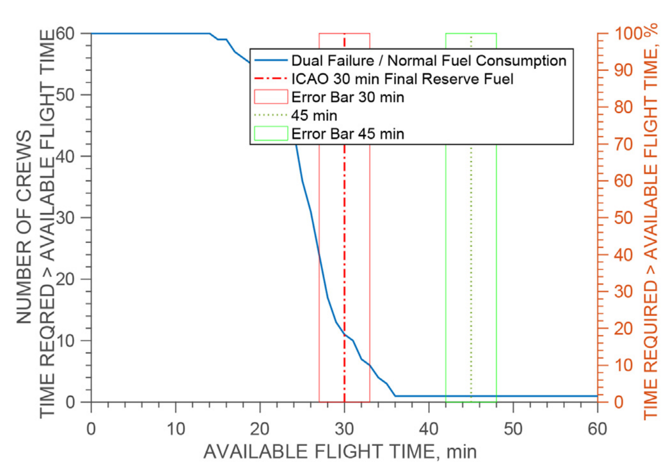

Fig. 4. Probability of fuel starvation (Case 1).

the red and green error bars (Fig. 4), to account for uncertainties: firstly, there may be a discrepancy between the indicated fuel and the usable fuel, which are roughly 3 min flight time (Langton et al., 2009). In the past, engine flameouts have been observed before the fuel quantity indication showed zero (CIAIAC, 2010). Secondly, regarding traffic at major airports, the route to the airport or speeds assigned by ATC may not correspond to the planned optimum, which is the basis for fuel calculation. By contrast, with 45 min of available flight time, the probability of fuel starvation is reduced to approximately 2%, a reduction of around 90%, assuming that $t_{Complex\ Failure}$ does not change.

Fig. 5 shows the probability of fuel starvation in *Case 2*. Due to the increased fuel flow $\dot{m}_{FuelFlow,increased}$, the probability that the time required for handling the complex failure exceeds the available flight time due to the amount of fuel increases to 85% for 30 min of available flight time within an error interval of [77%; 92%]. For example, the fastest crew (14 min, Fig. 3, right) requires fuel for at least 20 min due to the increased fuel flow.

However, with 45 min of available flight time, this probability is reduced to 10% with an error interval of [5%; 18%].

Finally, the $P(Crew\ Failure|Complex\ Failure)$ in *Case 3* is considered (Fig. 6). Here, seven additional minutes are subtracted from the observed flight times $t_{Complex\ Failure}$,

$$t_{Single\ Failure} = t_{Complex\ Failure} - 7min \qquad (13)$$

which was the average time required for pilots to handle the second abnormal event during the simulator experiments.

As indicated above, 27% with an error interval of [17%; 50%] of the crews would have needed more than 30 min of *Final Reserve Fuel* to solve the task. With 45 min of available flight time, this percentage is reduced to 2%.

Assuming that the three cases are representative of complex system failure events, the conditional probability of a fuel starvation, $P(Crew\ Failure|Complex\ Failure)$, is estimated by taking the average of the values of the three cases for each minute of available flight time. The authors are not aware of any investigations or data that would suggest weighting those three cases differently. The mean estimate of $P(Crew\ Failure|Complex\ Failure)$ and the 90% credible intervals to account for the uncertainties are calculated in a Bayesian analysis with a non-informative beta prior and binomial likelihood (Table 1).

43% of crews require more than 30 min to handle the complex failure scenario (abnormal) and an accident may be assumed. However, 3% of the crews would require fuel for more than 45 min to handle the abnormal. The time difference illustrates the need for an extra time added to the current 30 min *Final Reserve Fuel*.

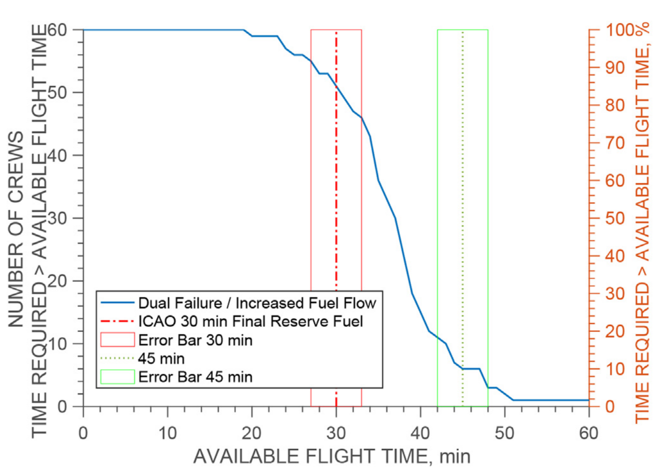

Fig. 5. Probability of fuel starvation (Case 2).

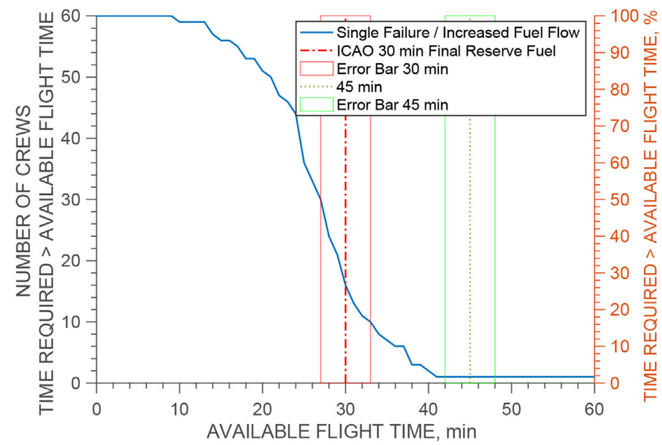

Fig. 6. Probability of fuel starvation (Case 3).

Table 1
Conditional fuel starvation probabilities for varying available flight times.

Final reserve fuel	Mean estimate	Credible interval (90%)
30 min	43%	[37%; 49%]
45 min	4%	[2%; 6%]

4. Risk assessment

4.1. Compliance with the ACARE-defined risk acceptance criteria

Following Section 2.2, the probability $P(Complex\ failure\ during\ approach)$ is in the interval of $[2.3\cdot10^{-8}; 3\cdot10^{-7}]$, with the best estimate being $8.3\cdot10^{-8}$. By multiplying this value with $P(Crew\ Failure|Complex\ Failure)$ from Table 1, an estimate of the accident probability $P(AT_{Complex\ Failure})$ is obtained (via Eq. (3)). The resulting estimates of the accident probability as a function of the *Final Reserve Fuel* are summarized in Table 2. Credible intervals are computed by Monte Carlo simulation.

As described in Section 2.1, the *acceptable* probability of an accident caused by a complex system failure should be in the order of $10^{-9} - 10^{-8}$, based on the ALoSP defined by ACARE. The results summarized in Table 2 provide a strong indication that the current 30 min *Final Reserve Fuel* is insufficient for complying with the ACARE safety targets. Taking the best estimate of $P(AT_{Complex\ Failure})$ under current regulations, $3.6\cdot10^{-8}$, the complex failure accident scenario alone would use up one third of the overall safety target $p_{target} = 10^{-7}$. As discussed above, an accident probability of $P(AT_{Complex\ Failure}) = 3.6\cdot10^{-8}$ is not sufficient to comply with the ACARE target, considering that there are other risks (accident types) on that same flight. An increase of the minimum required fuel upon landing (*Final Reserve Fuel*) from 30 min to 45 min leads to a reduction in the probability of this accident type by approximately one order of magnitude, leading to an acceptable risk.

4.2. Cost-benefit analysis

A cost-benefit analysis is performed to assess the costs of an increase of the *Final Reserve Fuel* in the light of the risk reduction. The risk reduction only considers an accident due to a complex abnormal situation resulting in fuel starvation. It does not consider other accident types.

Table 2
Accident probabilities for varying *Final Reserve Fuels*.

Final reserve fuel	Best estimate	Comparison with the *maximum* threshold level for a single accident type	Credible interval (90%)
30 min	$0.43\cdot 8.3\cdot10^{-8} = 3.6\cdot10^{-8}$	$> 10^{-8}$	$[9.7\cdot10^{-9}; 7.6\cdot10^{-8}]$
45 min	$0.04\cdot 8.3\cdot10^{-8} = 3.3\cdot10^{-9}$	$\leq 10^{-8}$	$[6.9\cdot10^{-10}; 7.6\cdot10^{-9}]$

In general, the higher the *Final Reserve Fuel*, the smaller the accident probability $P(AT_{Complex\ Failure})$. The change in the accident probability $\Delta P(AT_{Complex\ Failure})$ with *Final Reserve Fuel* t can be calculated as

$$\Delta P\left(AT_{Complex\ Failure}\middle|t\right) = P\left(AT_{Complex\ Failure}\middle|t\right) - P\left(AT_{Complex\ Failure}\middle|30min\right) \quad (14)$$

where $P(AT_{Complex\ Failure}|t)$ denotes the probability of a complex failure accident with t *Final Reserve Fuel*. For 45 min of available flight time, the reduction in the accident probability is

$$\Delta P\left(AT_{Complex\ Failure}\middle|45min\right) = P\left(AT_{Complex\ Failure}\middle|45min\right) - P\left(AT_{Complex\ Failure}\middle|30min\right) = 3.3\cdot10^{-9} - 3.6\cdot10^{-8} = -3.3\cdot10^{-8} \quad (15)$$

Reinsurance companies cover the (monetary) costs of an accident up to €2 Billion (Kuesters, 2014). This sum accounts for an accident with loss of life. An accident caused by fuel starvation inflight will most probably be fatal. On this basis, the risk reduction $\Delta R(t)$ as a function of the *available* flight time t is calculated as follows:

$$\Delta R(t) = -\Delta P\left(AT_{Complex\ Failure}\middle|t\right)\cdot € \, 2\cdot10^{9} \quad (16)$$

For 45 min of available flight time, the risk reduction equals $\Delta R(45\text{min}) = -(-3.3\cdot10^{-8})\cdot € \, 2\cdot10^{9} = 65\,€$, which is the gain of not having an accident due to a complex failure scenario.

Adding more fuel leads to a cost increase due to the additional fuel burn caused by the increased aircraft weight. We calculate the additional fuel burn and then evaluate its costs. For each additional minute t of available flight time, the aircraft weight increases by $\Delta m_{Aicraft}$, which is proportional to the aircraft's fuel flow *per minute*, $\dot{m}_{FuelFlow}$:

$$\Delta m_{Aicraft} = t_{additional}\cdot \dot{m}_{FuelFlow} \quad (17)$$

Based on the simulator data, we estimate $\dot{m}_{FuelFlow} = 46kg/min$ for a short-haul aircraft and $\dot{m}_{FuelFlow} = 170kg/min$ for a long-haul aircraft. Therefore, increasing the Final Reserve Fuel by 15 min, the additional aircraft weight equals $\Delta m_{Aicraft} = 15\cdot 46kg/min = 690kg$ for a short-haul flight and $\Delta m_{Aicraft} = 2550kg$ for a long-haul flight.

For every additional aircraft weight $\Delta m_{Aicraft}$, an additional amount of fuel per flight hour is burned that equals $k = 3\%$ of the corresponding additional weight (Ayra et al., 2014; EASA, 2016b). EASA uses this value as an average value for medium and large aircraft types. Therefore, the actual additional fuel burn $\Delta m_{\ Fuel\ Burn}$ can be estimated as follows, where $t_{Flight\ Duration}$ denotes the duration of the flight.

$$\Delta m_{FuelBurn} = \Delta m_{Aicraft}(t_{additional})\cdot k\cdot t_{Flight\ Duration} \quad (18)$$

For example, for 45 min of available flight time ($t_{additional} = 15\ min$) and the average flight durations in Europe (see Sec. 2.2), one gets:

$$\begin{aligned}\Delta m_{FuelBurn,\ Short-Haul} &= 690kg\cdot 3\%\cdot 1.4\ h = 29.0kg \\ \Delta m_{FuelBurn,\ Long-Haul} &= 2550kg\cdot 3\%\cdot 5.2\ h = 397.8kg\end{aligned} \quad (19)$$

To quantify the costs C for $\Delta m_{FuelBurn}$, we use the average fuel price of the last ten years, which is $P = 0.7163€/kg \approx 0.72\ €/kg$:

$$C = \Delta m_{\ FuelBurn}\ (t_{additional})\cdot P \quad (20)$$

The additional costs for $t = 45$ min are as follows:

$$C_{Short-Haul} = 29.0kg\cdot 0.7163€/kg = €\ 20.76 \quad (21)$$

$$C_{Long-Haul} = 397.8kg\cdot 0.7163€/kg = €\ 284.94 \quad (22)$$

Fig. 7 compares the risk reduction ΔR with the additional costs C in a function of the *Final Reserve Fuel* (within the range from 30 min to 60 min). The additional costs are shown for short-haul and long-haul flights, as well as for a mixed operation using the same ratio between short-haul and long-haul flights as in Section 2.2, i.e. 82.6% short-haul flights and 17.4.% long-haul flights.

Fig. 7 shows that with an increasing available flight time, the costs C and the risk reduction ΔR increase. The optimal *Final Reserve Fuel* is the one in which the increase in cost equals the increase in risk reduction. For short-haul flights, this point is reached at around $t = 45\ min$. For mixed operations, the optimal t lies within the range between 40 min and 45 min. Hence, for a short-haul operator

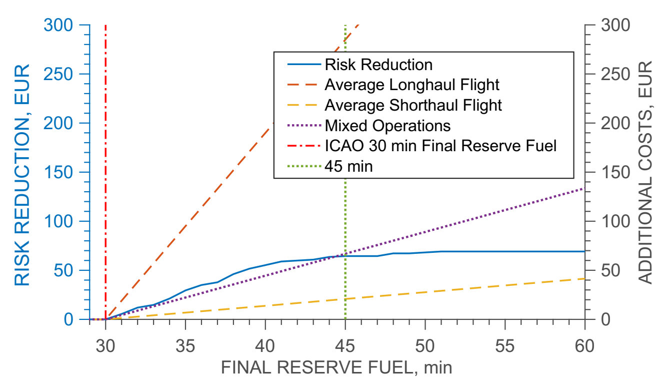

Fig. 7. Risk reduction versus cost.

with an average amount of complex abnormal situations, it is reasonable to dispatch and operate its fleet with a *Final Reserve Fuel* of 45 min. For long-haul flights, increasing the *Final Reserve Fuel* has a benefit-cost ratio below one.

The above comparison heavily relies on the fuel price, which may vary significantly over time (McConnachie et al., 2013). To study the effect of the fuel price on the cost-benefit analysis, we perform a sensitivity analysis. To this end, we calculate the benefit-cost ratio *BCR* for *additional* available flight time as follows:

$$BCR(t_{additional}) = \frac{\Delta R(t_{additional})}{C(t_{additional})}, \quad t_{additional} = 1, 2, \cdots, 30 \text{ min} \tag{23}$$

If *BCR* is greater than one, the reduction in risk is greater than the costs. Likewise, if it is less than one, the costs due to the additional fuel burn are greater than the benefit (risk reduction). For example, for the average short-haul flight, *BCR* equals for $t_{additional} = 15min$ (45 min *Final Reserve Fuel*),

$$BCR_{Short-Haul}(15\text{min}) = \frac{\Delta R(45)}{C_{Short-Haul}} = \frac{€\ 65}{€\ 20.76} = 3.1 \tag{24}$$

Fig. 8 shows the *BCR* against the *additional* flight time $t_{additional}$ for different fuel prices for a mixed-fleet operation, using the same ratio between short and long-haul flights as above (82.6% short-haul and 17.4% long-haul flights). We use the mixed-fleet operations because these are adequate to describe European air traffic. We consider fuel prices from the last ten years in order to capture its variability. During that period, the minimum price was US $39 per Barrel and the highest price was US $164 per Barrel (see Fig. A1). Fig. 8 also shows *BCR* for the average price (US $97.8) as well as the variations of one standard deviation (US $30.5).

Fig. 8 shows that for the average fuel price indicated by the magenta dot-dashed line, the costs start to exceed the risk reduction at 45 min (*BCR* becomes smaller than one).

Table 3 summarizes the cost-benefit analysis for 45 min of *Final Reserve Fuel*. We estimate the average costs for an individual passenger, because we assume that airlines would impose the additional costs on the passengers. The analysis is based on a passenger load factor of 80% and an aircraft with 164 seats for a short-haul and 326 seats for a long-haul aircraft. As Table 3 shows, the additional costs for a passenger are less than 1% of a ticket price, assuming, for example, €100 for a low-cost airline (short-haul) or €1000 for a long-haul flight.

4.3. Cost-effectiveness analysis

The cost-benefit analysis requires the cost of an accident as input. For regulatory purposes, when assessing life-safety risks, it is

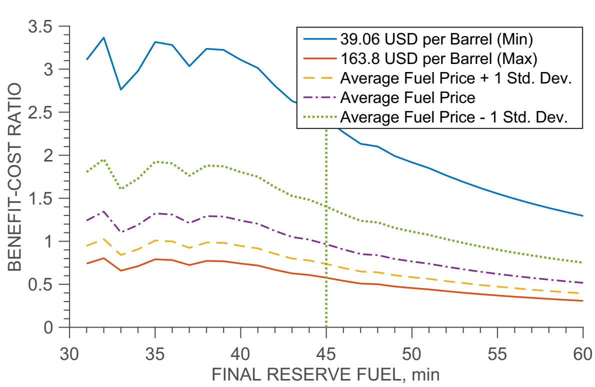

Fig. 8. Sensitivity analysis of the fuel price (mixed operations).

often preferable to compute the cost-effectiveness of corrective actions instead. This cost-effectiveness is commonly expressed in terms of the *Implied Cost of Averting a Fatality* (ICAF), defined as (Lewis, 2007):

$$ICAF = \frac{Net\ cost\ per\ passenger}{Reduction\ of\ life\ safety\ risk} \tag{25}$$

For the mixed-fleet operations and the average fuel price, the ICAF of extending the *Final Reserve Fuel* to 45 min is estimated as using the value from Table 3 and Eq. (15):

$$ICAF(45\text{min}) = \frac{€\ 0.32}{3.3 \cdot 10^{-8}} = €\ 9.7 \cdot 10^6 \tag{26}$$

I.e., extending the *Final Reserve Fuel* to 45 min implies an average cost of €9.7 Million (US $10.5 Million) to save a statistical life.

US regulatory agencies set the minimum ICAF value at around US $9 Million, which is the value per statistical life for the US (Robinson and Hammitt, 2015). If the costs of corrective actions are below US $9 Million, the corrective action is considered cost-effective. For the UK offshore industry, the ICAF is around £6 Million or €7.8 Million (Lewis, 2007). Given that the commercial airlines are very safe compared to most other industries, it is likely that the ICAF value of many implemented measures is well beyond these values. Therefore, it can be concluded that the extension of the final fuel reserve from 30 min to 45 min is a highly cost-effective measure for mixed operations, and would even be more effective when considering short-haul flights alone.

4.4. Ecological footprint of increased reserve fuel

The additional fuel burn increases the emission of CO_2. Every kg of fuel burned results in 3.16 kg of CO2. Given the additional fuel burn $\Delta m_{FuelBurn}$ (see Eq. (17)), the corresponding emission of CO_2 Δm_{CO_2} can be calculated as follows (EASA, 2016b; ICAO, 2016b):

$$\Delta m_{CO_2} = 3.16 \cdot \Delta m_{FuelBurn} \tag{27}$$

This amounts to around 91.6 kg CO_2 ($= 3.16 \cdot 29.0kg$) for a short-haul flight, which is roughly 1% of the CO_2 emission of the total flight. Likewise, for the average European long-haul flight, the additional CO_2 emission is around 1260 kg, or roughly 1% of the overall CO_2 emissions (see Table 4).

To put the additional CO_2 emission into perspective, it is compared to the CO_2 emission of an individual human. Assuming there are 131 passengers on a short-haul flight, the individual additional CO_2 emission is equal to 0.7 kg per flight and passenger. The normal CO_2 emission by a human being is about 0.05 kg/hour. During sport activity, the CO_2 emission increases to approx. 0.24 kg/hour. Therefore, the additional carbon dioxide emission corresponds roughly to 3 h of intense sport activity. In the long run, the additional emissions are compensated by the latest aircraft generation that promise up to 20% less fuel burn compared to the current generation (Airbus, 2016a; Boeing, 2016).

5. Discussion

5.1. Time to complete the scenario

It is sometimes argued that the measured times $t_{Complex\ Failure}$ observed during the simulator experiments are not representative for evaluating potential fuel starvations, as in real situations, humans would perform better than during the experiments. Several counterarguments may be presented in response to such argument.

Table 3
Cost-benefit for 45 min *Final Reserve Fuel* (fuel price = €0.72/kg).

Fleet	Risk reduction per flight, €	Cost per flight, €	Cost per passenger, € (80% Load factor)
Short-haul (84 min)	65	20.76	0.15
Long-haul (312 min)	65	284.94	1.09
Mixed-fleet	65	66.81	0.32

Table 4
Ecological footprint for 45 min of *Final Reserve Fuel*.

Fleet	Additional fuel burn per flight, kg	Additional CO_2 per flight, kg	Additional CO_2 per passenger and flight, kg
Short-haul (84 min)	29.0	91.6	0.70
Long-haul (312 min)	397.8	1257.0	4.8
Mixed-fleet	93.3	294.8	1.4

Firstly, terminating the experimental scenario more quickly would only have been possible by omitting parts of the abnormal procedures defined by the aircraft manufacturer. Disregarding abnormal procedures to save a few minutes can trigger an increase in the risk: one total loss could be observed in the experiments, caused by the flight crew's decision to omit ECAM procedures.

Secondly, Airbus and Boeing recommend consulting the Expanded Abnormal Procedures before landing when experiencing a technical malfunction. This recommendation cannot be followed if only half an hour is available for problem-solving as the simulator study shows.

Thirdly, after completing the experiments, all crews stated in an interview that they worked as *quickly as possible* and reported the feeling of time pressure. Previous research, e.g. from the nuclear industry, has indicated that time pressure positively correlates to the number of human errors (Podofillini et al., 2013; Swain and Guttmann, 1983). In general, one would therefore expect an increase in the number of human errors rather than an improved performance due to the time pressure. The increase of erroneously executed procedures requires additional flight time, as these errors have to be corrected by the crew. The interviews also showed that the limited time available for problem-solving increased the stress level of some participants dramatically, and had negative effects on team interaction, failure recognition and decision-making.

One may also argue that improved or additional training of pilots would serve as an alternative corrective action, instead of increasing the amount of fuel. However, all pilots participating in the experiments were trained at the in-house flight school of the considered airline, after having passed specific selection tests by the German Aerospace Center (DLR). Similar tests are applied to air traffic controllers, in which large-scale studies show a positive correlation between the selection criteria and the student's future performance (Conzelmann et al., 2011; Pecena et al., 2013). In addition, all pilots received more training by the airline than legally required and recommended by the manufacturer, which suggests that purely increasing the amount of training is not a sufficient corrective action for this kind of problem. In order to train pilots to handle these kinds of scenarios in a faster manner, new training concepts are required whose effectiveness would also need to be demonstrated. Accordingly, such new training concepts as an alternative corrective action cannot be implemented immediately and may require additional years of research.

Realistic time requirements – in terms of the average flight crew performance – should be taken into consideration when fuel limitations are defined. The 45 min *Final Reserve Fuel* is justified considering safety, economic, and ecological needs. Between July 2015 and June 2016, the percentage of flights landing with between 30 min and 45 min of fuel remaining was only 0.02% within the considered airline. This illustrates that the proposed mitigation strategy fulfills the ICAO requirements for corrective actions, e.g. practicality and effectiveness (ICAO, 2013b), and can be implemented *today*.

5.2. Recommendations for a new fuel policy

No aircraft should land with less than 45 min remaining flight time, except after having encountered a technical problem during the final stage of a flight. Landings with less than 45 min should require a mandatory report to the authorities in order to allow EASA to assess the actual fuel starvation risk within Europe.

The planned arrival fuel for any destination should be 45 min of *Final Reserve Fuel* plus alternate fuel or at least 15 min (plus *Extra Fuel* to account for the traffic situation at the destination airport) when operating without an alternate airport. This means that the minimum arrival fuel should be at least 1 h (plus *Extra Fuel*) at any destination.

One hour of standard arrival fuel gives an averagely performing flight crew the chance to solve a complex technical problem. Nevertheless, if high traffic is expected and/or the weather forecast is critical, more *Extra Fuel* is required.

6. Summary and conclusions

In this paper, we have shown that the current regulations stating that the *Final Reserve Fuel* must allow for 30 min of flight time cannot guarantee that an averagely performing flight crew will successfully handle complex failure scenarios. Three cases with varying fuel flows and degrees of complexity are considered. Our timeframe measurements were taken from two simulator experiments, during which crews handled abnormal procedures arising from a green hydraulic failure in combination with a flap problem. We showed that 45 min would be sufficient to reduce the fuel starvation probability by approximately 90% or one order of magnitude, which supports the aim of Europe to reduce the accident rate (European Commission, 2015).

The actual minimum fuel requirements defined by ICAO/EASA may be sufficient if the present accident rate is accepted. However, as this analysis shows, the current fuel policy is not sufficient to guarantee the long-term safety target for Europe. The very competitive situation in the airline market incentivizes the use of creative interpretation and circumnavigation of existing requirements in order to achieve small cost reductions by decreasing the fuel uplift. Therefore, it is reasonable to assume that airlines under high cost pressure will use strategies to reduce the arrival fuel to below 45 min, if legally permissible. For example, regularly using the alternate fuel to cover *expected* delays during the flight is not desirable, but is also not illegal under current legislation. Today, fuel emergencies already occur particularly often when air traffic is affected by external disturbances, such as thunderstorms or unexpected traffic congestion (CIAIAC, 2010; Hradecky, 2016).

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APPENDIX

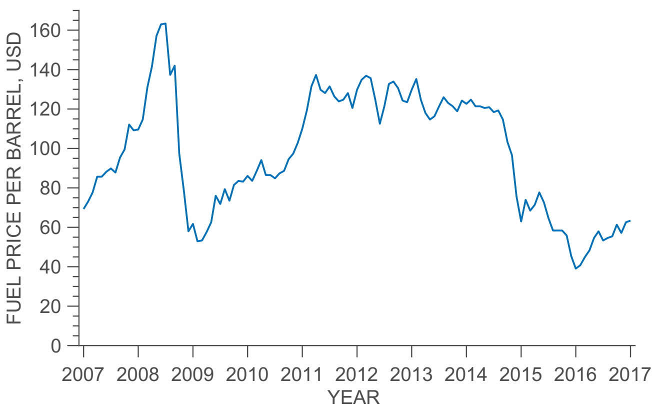

Fig. A1. Fuel price (IndexMundi, 2017).

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