Delays and safety in airline maintenance

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Abstract

Airline maintenance operations affect the potential for flight delays and can also affect flight safety if signals of technical problems are missed or misinterpreted. In this paper, we use a probabilistic risk analysis model, represented by an influence diagram, to quantify the effect of an airline’s maintenance policy on delays, cancellations and in-flight safety. The model represents the leading edge (LE) sub-system of a commercial passenger jet and consists of three tiers: (1) a set of management decision variables (e.g. the level of qualification of maintenance personnel); (2) a ground model linking policy decisions and flight delays; and (3) an in-flight model, linking policy decisions, maintenance quality and flight safety. To illustrate this model, we use data adapted (for confidentiality reasons) from a study of an existing airline. Clearly, the LE devices of an airplane are not among the most safety-critical and the risk of an accident due to poor maintenance is extremely small, but non-zero. The same model can be used for other, more critical parts of the aircraft to support maintenance policy decisions in which the trade-off between delays and safety may be more pronounced. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Management of airplanes between flights

Flight delays often occur because a problem detected in the previous flight needs to be fixed before the next take-off. Some of these problems are minor, others can affect flight safety and proper maintenance becomes critical. Airline managers make a number of decisions that may affect the quality of maintenance, and these decisions can have an effect both on delays and safety. Trade-offs might therefore occur, and it may be useful to identify and quantify them to support these decisions.

Over the past decades significant improvements in airline safety have taken place [1]. At the same time, air travel in the US has increased from 95 million passengers in 1965 to 547 million passengers in 1995 (FAA Safety Statistics, Safety Records of US Airlines, Part 121), and many airports now operate at full capacity. Nevertheless, passengers expect affordable service on schedule. As a result, US carriers are trying to achieve high standards of safety and service at minimal cost. Flight delays and cancellations are critical measures of quality of service.

In this paper, we present a model designed to assess the effects of between-flight repairs, both in terms of delays and safety. To illustrate this model we focus on the unplanned maintenance of the Leading Edge (LE) device system of a hypothetical aircraft that we call here the IJK. The data we use were gathered for a particular airline [2], then changed in this illustration for reasons of confidentiality to represent the case of a hypothetical airline that we call here XYZ.

1.1. The constraints of delay and safety

The increased sophistication of today’s commercial airplanes calls for specialized service personnel whose availability varies among airports and aircraft (e.g. B757, B777 or A320). This decreases the likelihood of being able to repair unforeseen problems and increases the likelihood of delays.

During the phase of problem detection in maintenance, cognitive errors become an issue. An existing problem can be misclassified as “System OK” (Type I error)—or a part that meets specifications can be wrongly classified as dysfunctional (Type II error). The occurrence of a Type I error can decrease the safety of an aircraft because the undetected or misclassified problem can cause an incident in flight. A Type II error can increase the likelihood of a delay because the maintenance crew will have to address a non-existent problem. Other types of errors can occur during maintenance operations, e.g. the use of a wrong part or damaging other parts of the LE system. These errors
are not considered specifically in our illustration, which is limited to failures to identify and address existing problems.

1.2. Current standard practice

Current standard practice for airplane maintenance is a three-step process. First, a problem is identified and reported by the flight crew by means of a pilot report (“pilot’s write-up”). Second, once the plane arrives at an airport, troubleshooting (“verification”) is performed on the reported problem. Third, problems that have been confirmed are repaired.

All pilot reports are communicated to the flight’s destination airport, and a local maintenance crew is informed. If a maintenance crew is available when the plane lands, they inspect the plane and confirm or not the pilot’s write-up. Any confirmed problem is then classified into “deferrable” or “not deferrable”. Deferrable items are those that are non-critical to airplane safety (e.g., indicator light for one LE slat broken, see Appendix A1). Each deferral can only be carried for a limited time. If the component is not repaired during that time, regulations of the Federal Aviation Administration (FAA) will ground the plane. Airlines set goals for the allowed number of deferrals carried by a particular type of aircraft. Deferred items are repaired and taken off the list of deferrals whenever there is time to do so, generally during the night shift.

All confirmed and non-deferrable items have to be repaired before the next departure. This includes any additional problem that is discovered during troubleshooting and maintenance. After all necessary repairs have been completed, an FAA-certified mechanic checks them and verifies that all regulations are met. The aircraft is then handed over to the flight crew. At this point, the pilot performs a walk-around check of the plane. If he is not satisfied with the status of the plane, he can decline to fly it. Otherwise, the flight crew will initiate boarding procedures and the plane takes off.

1.3. The role of a probabilistic risk analysis

A key issue in the management of unplanned maintenance operations is to ensure the safety of the airplane while keeping delays to an acceptable level. It is thus useful to assess the effect of maintenance decisions on flight delays and on the risk of an in-flight incident. Whereas it is generally assumed that an airplane that satisfies regulatory or company requirements has a zero probability of an accident, the fact is that combinations of rare events, errors and undetected departures from the rules do rarely, but occasionally, cause a plane crash. Reliability data are useful to check that proper working requirements are satisfied. A more sophisticated analysis is needed to identify scenarios that can lead to an accident. To that effect, we use, in this paper, a probabilistic risk analysis (PRA) (see for example, [3–6], Henley and Kumamoto 1981) and its extension to include management factors (e.g. in [7]). The approach taken here is similar to that used for other types of technical or medical systems such as the space shuttle, anesthesia in operating rooms, and offshore platforms of the oil and gas industry (Paté-Cornell 1990, [7,8]).

In airplanes, as in many complex engineering systems, single problems or errors rarely lead to technical system failure. Instead, a conjunction of problems that are difficult to observe can constitute a failure mode (e.g. Challenger disaster in 1986). Some of these failure modes do include operator errors. In most cases, however, human errors (e.g. in maintenance operations) do not enter directly into these failure modes, but affect the probabilities of their elements. One can therefore distinguish the technical system from the human and management system to which it is subjected, and describe in quantitative terms the probabilistic dependencies between the two [7]. In the context of airlines, accidents do occur because of conjunctions of sometimes minor events, both technical and organizational in nature (e.g. lapses in the complex flight-control systems, errors in maintenance procedures, and human misjudgments). Our model shows how some human and organizational factors in maintenance operations affect both the distribution of flight delays and the probabilities of the failure modes of the LE devices in flight. Therefore, it can help the decision makers manage the possible trade-offs involved.

1.4. Scope and procedures of the study

In a study for a US airline [2], we used probabilistic risk analysis to analyze the effects of maintenance decisions regarding the LE sub-system for a specific aircraft type on delays and cancellations of flights as well as flight safety. Clearly, the LE devices of an airplane are not among the most safety-critical and the risk of an accident due to poor maintenance is extremely small, but non-zero. Because the LE sub-system has never caused an accident before, reliability data are of little use while PRA can provide some insights. Starting with an analysis of the LE flaps and slats, we added to the model a layer of management decisions that have a direct effect on the maintenance operations of the airplane. The model and the modeling process are described below. The original data used in the model were based both on expert opinions and statistics gathered in the airline’s computerized system, which consisted of two databases. One contained verbal descriptions of the maintenance performed, and the other numerical data downloaded directly from the plane’s computer system. For reasons of confidentiality the illustrative data used in this paper are modified versions of those originally gathered.

Similar data can be found in the databases of most airlines. Expert opinions that are relevant to our models have to be elicited for the considered airline, aircraft and perhaps airport type. In the original study, they were encoded in a three-step process following the
guidelines set by Morgan and Henrion [9]: First, we introduced the experts to the general task of data elicitation. In doing so, we made sure that they were aware of cognitive pitfalls of this process [10]. Second, we developed clear and unambiguous definitions of the variables that had to be assessed. During this phase, we also identified any unstated assumptions that the experts could make. Finally, the experts assessed the data for the variables in question.

Based on these data, we developed a three-tier model. The first one represents management policies and decisions, the second their effect on maintenance and delays, while the last one describes the effect of management policies and ground maintenance on in-flight safety. Conditional on management policies, the ground-delay model yields a probabilistic description of delays and flight cancellations (delays of more than 3 h). The in-flight model yields a probability distribution for events in flight (nothing, severe shaking or crash). The two models are related first by their dependence on management policies, and second, because management decisions can have an effect on the probabilities of in-flight incidents: less time for troubleshooting decreases the chance of a delay but can marginally increase the probability of an incident in flight. This three-tier model is then evaluated to yield probability
distributions, both for delays and for events in flight. We simulated a wide range of scenarios using Latin–Hyper–Cube sampling.

2. Model structure

2.1. The leading edge slat system

LE devices are used in combination with the trailing-edge flaps to allow airplane operations on short runways. The airplane can still fly and land without the LE system but this would require a longer runway. A failure of the LE system occurs when the slats/flaps do not extend or retract as needed. In particular, if slats/flaps extend or retract asymmetrically (i.e. only on one wing and not on the other), the airplane will turn around its longitudinal axis and “roll”. Should this occur in flight, the pilot will then balance the plane using the rudder and elevation control, generally without any problem. An LE system failure is only critical if the plane is close to the ground because it could lose altitude during final approach or not produce enough lift during take-off.

The extension/retraction of slats and flaps can be observed from the cockpit, or by means of a display system located above the pilot’s head. It is triggered by proximity sensors located on each leading-edge flap and slat, and can be monitored both by the pilot and the co-pilot. The display system’s electronics are located in an electronics module in the cockpit and can be replaced easily. Therefore, if the display system is not working properly, mechanics often change the whole module instead of trying to identify the source of the problem within the module. The LE system integrates electronic, hydraulic and mechanical elements, which represent multiple error sources. In particular, the exposure of electric sensors to the outside environment makes these devices prone to errors.

2.2. The three-tier model

Our model, as described above, is implemented as a three-tier influence diagram [11,12]. The link between the ground model and in-flight model is especially important in the presence of undetected maintenance errors. We do not consider scenarios where maintenance errors in the LE system damage other parts of the aircraft. We consider the other sub-systems of the aircraft only to the degree that the conjunction of an LE incident and a malfunction elsewhere could cause an unwanted incident in flight. The ground model is conditioned on the occurrence of an LE write-up. For the in-flight model, three types of incidents can put the aircraft at risk: external events; random system failures (unconnected to previously observable problems); and incidents due to a Type I error during maintenance (misdiagnosed or incorrectly repaired problem).

Fig. 1 shows the influence diagram that represents the overall model. For the ground model, the result of interest is “Delay Distribution” which is characterized by the probability distribution of the length of delay and the probability of flight cancellation. The variable of interest for the in-flight model is “Flight Outcome”, which is characterized by the probability distribution of unwanted outcomes (severe shaking or crash). What follows is a description of the model structure. A more detailed discussion of each of the model’s variables and parameters can be found in Appendix A.

3. Linking management decisions to maintenance and flight performance

3.1. Management and maintenance

The ground model is represented by the middle tier of the influence diagram in Fig. 1. Management can affect the maintenance procedures in many different ways, directly or indirectly, and maintenance, in turn, affects delays and safety. We focus here on three types of decisions only (many others could be considered): qualification of maintenance personnel; number of deferrals allowed; and timing of maintenance operations.

Qualification of maintenance personnel. This decision variable influences the quality of maintenance. A maintenance crew can be very thorough at the cost of increased work time or can work more swiftly, but perhaps less precisely. Maintenance managers can thus face a trade-off between minimizing maintenance time and maximizing safety.

Timing of maintenance operations. The time at which maintenance crews are required to start working on a newly arrived plane varies. In general, their work starts immediately on planes with short layovers while planes with longer layovers may have to wait. Requiring that maintenance crews start working on an airplane immediately after it arrives gives them more time to locate and correct problems. Because of large numbers of aircraft arrivals and departures from major airports, the optimal scheduling of maintenance services poses a challenge or requires an increase in personnel.

Number of deferrals allowed. This decision variable is specified by the airline based, for example, on an average calculated for the whole fleet. We did not represent in our model the FAA limitation of the time during which a deferral can be carried on a plane because we did not model multiple time periods.

Once maintenance personnel locates and classifies a problem as non-deferrable, the availability of parts and maintenance capabilities becomes a constraint. Different airports provide different inventories of spare parts and different levels of maintenance skills. Also, the scheduled layover time varies from airport to airport, as does the availability of spare planes, which avoids maintenance delays.

The actual time necessary for maintenance is thus
determined: (1) by the standard maintenance time needed to solve a particular problem; (2) by the availability of parts and labor; and (3) by the confirmation time (a pilot write-up has to be confirmed and classified, before a maintenance crew can start its work). In our model, actual maintenance time is the sum of the time needed for confirmation and classification of the problem, standard maintenance time needed for this type of problem, and time penalties in cases where necessary parts or labor (or both) are not immediately available.

A delay occurs if the time needed for maintenance plus the time elapsed before maintenance starts is larger than the layover. Maintenance time, however, can be zero in the following situations: (1) the problem item can be deferred; or (2) a spare plane is available at the airport and can be used instead of the plane that needs to be repaired (we did not consider here the time needed to switch planes). Again, if a delay extends to more than 3 h, we assume that the flight will be cancelled.

3.2. Management, maintenance and flight performance

If the LE system experiences an undetected problem and an in-flight incident occurs, the roll of the plane can be handled by the pilot, most of the times without any problem. One could conceive, however, very rare cases in which a minor LE incident, compounded with a human error, a simultaneous failure elsewhere or a conjunction of bad weather and low altitude, could lead to an accident. The in-flight model is represented by the lower tier of the influence diagram shown in Fig. 1.

The model analyzes the probabilities and the consequences of unanticipated events due to failure of the LE system during flight. The model’s outcome is based on five variables as shown in Fig. 1. It is coupled with the ground model through the variable “LE Problem Manifestation” which is conditioned on “Confirmation” and “Random LE Failure”. It is also influenced by the decision variable “Qualification of Maintenance Personnel”.

Two sources of LE failures are considered here: random failures, which occur sporadically and are not linked to maintenance, and failures that result from maintenance errors (omissions or Type I). “Qualification of Maintenance Personnel” in this model can be characterized as “standard” or “increased”. If it is set to “standard”, there is a non-zero probability of a Type I error. If it is set to “increased”, Type I errors are assumed not to occur but maintenance will take longer. Only random errors can then occur. We assume that Type I errors and random errors cannot occur simultaneously but we include the possibility of concurrent failures of other plane systems.

As described above, the presence of an undetected problem in one of the aircraft’s LE devices increases the probability of a malfunction and of an event in flight (severe shaking of the plane or, in very rare instances, a crash). Given the occurrence of an LE incident in flight, the relevant variables for the flight outcome are: the altitude of the plane, the possibility of simultaneous failures of other systems, the weather, the reaction time of the pilot and the action he takes. Given such an incident, the reaction time of the pilot is crucial and the pilot’s reaction itself may be appropriate or not, depending on his experience [13]. In effect, LE incidents should have very little impact on the overall accident risk. Again, there has never been so far an accident of that kind. Two factors, however, are critical to the LE system’s small contribution to the risk: whether such an incident occurs at take-off or landing; and whether it is compounded by a severe pilot error or simultaneous failure of another system.

4. Results

The results of this study are twofold: findings from the modeling process itself, and numerical insights from the illustrative results of computations. Again, the data used here have been modified for confidentiality reasons. In the model, we assumed that the aircraft has an LE problem when it arrives at the gate. Therefore, the results that we show are conditional probabilities of delays and accidents given the occurrence of an LE problem to which we assigned a probability in the order of $10^{-3}$ per flight cycle.

4.1. Database problems

In the process of building the model, it became apparent that airline maintenance software, which was developed decades ago but is still often used today, poses problems to many carriers. The software problems, in turn, can be a source of maintenance deficiencies. This software is generally used to collect and store data about flights and aircraft. The data gathered, however, are not compatible (or only with difficulties) with modern software, which makes data analysis more difficult. This is true for instance, if one of the databases contain verbal descriptions of repairs and maintenance for all airplanes while another contains statistics of repairs and maintenance operations for a specific type of aircraft. Another problem that can complicate the modeling process is the lack of standard terminology for use in problem write-ups. Different maintenance personnel use different words for identical items, which can lead to confusion when the data are analyzed.

4.2. Model insights

The model presented here can help managers assess the effect of their decisions both on delays and flight safety, and answer the following questions:

- Which decision variables are most relevant to delays?
- What is the distribution (and the mean) of delay times and the probability of a cancellation?
- What is the trade-off between delays and flight outcomes?
To address the first question (relevant decision variables), we ran the model for different settings of the decision variables and recorded the distribution of delay times and flight safety. The mean delay was calculated conditional on delay times of less than 3 h.

In our model, the decision variable that has the most significant impact on delays and cancellations is maintenance quality. For the limit case of “increased” (perfect) maintenance quality, the estimated mean delay ranged from 108 min (up to 2 deferrals per plane, maintenance starts immediately) to 140 min (up to 5 deferrals per plane, maintenance starts immediately). For this maintenance quality, the probability of a flight cancellation conditional on a LE problem at arrival would average 0.69 (therefore a marginal probability in the order of $10^{-3}$). For “standard” maintenance quality, the mean delay, conditional on an LE problem at landing, ranged from 103 min (up to 2 deferrals per plane, maintenance starts immediately) to 107 min (up to 5 deferrals per plane, maintenance starts immediately). In this case the conditional probability of a flight cancellation averaged 0.27, thus yielding a marginal probability in the order of $10^{-4}$.

To address the second question (shape of the distribution of delay times and probability of cancellation), we generated the distributions of delay times as a function of the settings of the decision variables. Tightening any of the constraints represented by the decision variables moves the distribution of delay times to the right (see Fig. 2).

To address the third question (trade-offs between delay and safety), we compared the distributions of delay times and flight outcomes for two sets of assumptions regarding the quality of maintenance. If qualification of maintenance personnel is set to “standard”, we allow for errors in confirmation. We simulated 45,000 flight-cycles, conditional on the presence of an LE problem at arrival at the gate. The results based on our hypothetical data can be summarized as follows:

- For 45,000 flight cycles with an LE problem at gate arrival, the number of delays is found to be 18,073 for a maximum of 5 deferrals per plane, “strict” timing of maintenance operations and “standard” qualification of maintenance personnel, resulting in a conditional probability of delay of 0.4. It is 3,772 for a maximum of 2 deferrals per plane, “tolerant” timing of maintenance operations and “increased” qualification of maintenance personnel, resulting in a conditional probability of delay of 0.084, with a probability of cancellation of 0.76.
- Given that a delay occurs and does not result in a cancellation, its mean duration is found to be 140 min for a maximum of 5 deferrals per plane, “strict” timing of maintenance operations and “increased” qualification of maintenance personnel. The corresponding probability of cancellation is 0.64. The conditional mean of the length of delay is 104 min for a maximum of 2 deferrals per plane, “tolerant” timing of maintenance operations and “standard” qualification of maintenance personnel, resulting in a conditional probability of cancellation of 0.31.
- The decision variable qualification of maintenance personnel has a significant effect on delay distribution and only a marginal effect on the probability of an accident (flight outcome). A trade-off between delay time and flight safety can be observed but it is small (the variation in our illustrative example is in the order of 1%). In our example, we found that for “standard” maintenance procedure the risk of an accident conditional on an LE problem at gate arrival is 6.7 in 45,000 flight cycles, resulting in a conditional probability of accident of $1.48 \times 10^{-4}$ and a marginal probability in the order of $10^{-7}$. In the limit case of a “strict” (“perfect”) maintenance policy, the risk of an LE maintenance-induced crash is reduced only to 6.6 per 45,000 flight cycles, resulting in a conditional probability of accident of $1.46 \times 10^{-4}$ and again, a marginal probability in the order of $10^{-7}$. These illustrative numbers are clearly
higher than the actual ones given past experience. In reality, LE problems are minute contributors to the chances of a plane crash, the overall probability of which historically is in the order of \(10^{-3}\) per departure [1].

- The number of deferrals allowed and timing of maintenance operations (in that order) have less effect on delay and flight safety than maintenance quality.

5. Conclusions

This model illustrates the use of probabilistic risk analysis to assess the effects of specific management decisions concerning maintenance of a sub-system of a particular type of plane both on airplane delays and on flight safety. The model helped us to assess quickly the effects of different management strategies. Managers can use this information system in meetings for real-time decisions. It permits identifying the parts of the maintenance system that need to be upgraded in priority depending on the airline’s strategy and the area in which it operates. For example, an airline manager may want to ensure that spare parts and maintenance skills are available in the small airports where delays might cause a bottleneck in down-stream operations.

According to our model, one can observe a marginal trade-off between minimizing delay and maximizing safety as far as the LE system is concerned. But, the rate of LE problems is so low (about \(10^{-3}\) per flight cycle) as is the probability of an accident conditional on such a problem, that the safety aspect of the trade-off is marginal. This explains why an LE-induced accident has not occurred yet, which of course doesn’t mean that it will not happen in the future. Indeed, it could happen if an incident in flight caused by an LE maintenance error occurred at takeoff or landing, if a pilot error compounded the problem, or if an other failure occurred at the same time. Clearly, the LE system is not among the most critical ones in the aircraft. Using this model for more critical systems (e.g. hydraulic manifolds) would probably show a more significant effect of maintenance quality on flight safety.

The limitations of the use of this model will lie first in the completeness and accuracy of the model structure (choice of variables and parameters) and second, in the estimation of the data. Managers will have to rely first on the statistics available in the airline databases and reconcile the different types of information that they contain. They will also have to use the opinions of the best experts of their airline. In particular, the experts will have the difficult task to estimate the effects of policies on human performance before they have had the opportunity to observe them directly. They may, however, have had the benefits of previous experience that may be valuable when estimating the impact of policy changes.

The advantage of such an analysis over an intuitive estimation of the results is that it allows combination of the different factors and therefore, an assessment of the influence of each of them on the probability of the different outcomes. It can also be a useful communication tool in management discussions of maintenance policies, and show the sensitivity of the results to different numerical assumptions. Risk analysis models, like the one presented here, can thus be the basis for information systems designed to support both technical and managerial decisions aimed at making commercial air travel safer, more reliable, and more profitable.

Appendix A. Detailed model description

A.1. Ground-delay model for the leading edge devices

The following section contains the qualitative description of each variable of the ground model influence diagram for the LE system.

1. **LE problem write-up.** This random variable represents the nature of the problem conditional on the presence of an LE problem when the aircraft arrives at the gate. Its realizations are: mechanical problem, hydraulics problem, switches/electrical problem. The frequencies of each realization are: mechanical problem, hydraulics problem, switches/electrical problem. This information is available in airline maintenance databases.

2. **Confirmation.** Confirmation refers to the process of determining the actual problem given a write-up (realizations: no problem, electrical, mechanical or hydraulic problem). It is characterized by the conditional probabilities of the actual problems, given the detected ones. This information is available in airline maintenance databases.

3. **Confirmation time.** Given a suspected problem, this variable represents the time needed to troubleshoot and confirm the problem. We assumed a lognormal distribution [14]. The parameters of the distribution depend on the realization of the decision variable “Qualification of Maintenance Personnel”. They have to be estimated by airline experts. Note that if \(p_x\) represents the \(x\)th quartile for “standard” and \(q_x\) represents the \(x\)th quartile for “increased” maintenance quality, then \(p_5 < q_5\) and \(p_{95} < q_{95}\).

4. **Standard maintenance.** This variable represents the time needed to solve a problem once it has been confirmed and classified. We assumed a lognormal distribution that depends on the decision variable “Qualification of Maintenance Personnel”. The parameters of this distribution have to be estimated by airline experts.

5. **Location.** This variable represents the type of airport where the problem is confirmed and repaired (if possible). We defined three airport types, depending on availability of parts and maintenance skills, as shown in Table A1.
The probability of being in a certain airport type can be calculated from data contained in the airline’s flight schedule.

6. Layover. Layover is defined as the time between the plane’s planned arrival at the gate and its planned departure (scheduled layover). Its distribution can be derived from the flight schedule.

7. Timing of maintenance operations (TMO). This decision variable determines how soon the maintenance process is initiated after a plane’s arrival at the airport. Its realizations are: “Strict” or “Tolerant”. Under a “Strict” policy maintenance starts as early as possible (“gate-in philosophy”). Under a “Tolerant” policy, maintenance is initiated based on “scheduled departure time minus standard maintenance time” (“gate-out philosophy”).

8. Start maintenance. This variable is defined as the time elapsed between arrival of a plane carrying a pilot’s write-up and the start of the maintenance process. Given “strict” TMO, this time is always assumed to be zero. Given “tolerant” TMO, this time is zero for short layovers (60 min or less) but is positive and increasing for longer layovers (uniform random variable). This distribution has to be assessed by airline experts based on practice.

9. Spare plane availability. This variable (realization “yes” or “no”) is conditional on “Location” as described above. The corresponding probabilities can be found in airline databases.

10. Parts availability. This variable represents the time needed to obtain the parts necessary to perform maintenance. Its distribution is conditional on “Location” and “Confirmation”. We assumed it to be lognormal (ibid.) with parameters to be assessed by airline experts.

11. Maintenance availability. This variable describes the time needed to obtain the personnel with the required skills. Its distribution is conditional on “Location” and “Confirmation”. It is assumed to be lognormal (ibid.). Again, its parameters have to be estimated by airline experts.

12. Actual maintenance time. This deterministic variable represents the time needed to complete the maintenance process and it is defined as:

\[
\text{Actual maintenance} = \text{Confirmation time} + \text{Standard maintenance} + \text{MAX(Parts availability, Maintenance availability)}.
\]

13. Deferrals on list. This variable represents the number of deferred problems already carried on an airplane. We assume a Poisson Distribution with a mean of 2 which implies that approximately 5% of all aircraft carry 5 or more deferrals, which seems consistent with current experience and may have to be adjusted based on existing data in specific airlines.

14. Deferrable? This variable (realization: “yes” or “no”) is characterized by the probability that the confirmed problem can be deferred according to the rules of first and foremost the FAA, then the airline (which might have additional guidelines) and finally the pilot (if he is not satisfied with the status of the aircraft—e.g. indicator light for one LE slat broken; the probabilities of “deferrable given confirmed problem type” are 0.1 for mechanical, 0.05 for hydraulic and 0.3 for electrical problems in the LE system).

15. Number of deferrals allowed. This decision variable has four possible realizations: 2, 3, 4 or 5 deferrals.

16. Defer. This deterministic variable has two possible realizations, “yes” or “no”. Repair can be deferred if; (1) the problem is deferrable; and (2) the total number of deferred problems on that plane does not exceed the number of deferrals allowed.

17. Delay. This is a deterministic variable. If a spare plane is available, or if the problem can be deferred, or if the time required for maintenance is less than the time available (layover time minus time of maintenance initiation), there is no delay. Otherwise, the delay is equal to the actual maintenance time minus the time available and is characterized by the distribution of the difference.

18. Qualification of maintenance personnel. This decision variable has two realizations: “increased” and “standard”. “Increased” represents a limiting case where we assume the feasibility (at a cost) of perfect maintenance (no errors).

A.2. In-flight model for the leading edge devices

The in-flight model describes the technical, human, and environmental factors that affect the probability of unwanted flight outcomes, given an LE problem. Relevant data resulting from the ground delay model enter the in-flight model as information about the prior probability of a problem in the LE slat system and the node LE Problem Manifestation.

1. Random LE failure. This random variable represents a technical failure of the LE system that is not caused by improper maintenance (realizations: “yes” or “no”). Its probabilities can be based on statistics available to the airline.
2. **LE problem manifestation.** This random variable has three realizations: “mechanical problem”; “hydraulics problem”; and “electrical problem”. The probabilities for each of these events can be obtained from the airline’s maintenance database. If “Qualification of Maintenance Personnel” is set to “standard”, a Type I error can occur.

3. **Incident due to LE.** This discrete random variable is conditioned on “LE Problem Manifestation” and has three realizations: (1) “Not able to extend LE slats”—LE cannot be extended over 20°; (2) “Not able to retract LE slats”—LE cannot be retracted under 20°; and (3) “No indication of existing problem”.

4. **Timing of signals.** This discrete random variable represents the time elapsed between the occurrence of a problem and its detection by the pilot. It has three realizations: (1) “0–1 min”; (2) “1–4 min”; and (3) “more than 4 min”. It is conditioned by the event “Incident due to LE”. The data can be obtained through interviews of pilots and possibly by analysis of past incidents or experiments using flight simulators.

5. **Pilot’s experience.** This random variable has two realizations: (1) “0–1 year” and (2) “more than 1 year”. The corresponding distribution can be found in airline data.

6. **Pilot’s action.** This random variable has two realizations (“appropriate” and “inappropriate”). It is conditioned on “Pilot’s Experience” and “Incident due to LE”. The distribution can be best assessed by the pilots themselves.

7. **Weather.** This random variable has two realizations (“icing” and “no icing”). The probabilities can be derived from existing statistics. For the sake of simplicity, we did not condition it on location and time of year and used a marginal distribution.

8. **Altitude.** This random variable has three realizations (“take off”, “cruising” and “landing”). It is relevant because it affects the pilot’s margin for maneuvering in case of a leading-edge incident. The probability of the three realizations can be derived from distributions of the duration of each flight phase for the considered plane in a given airline.

9. **Simultaneous failure.** This random variable has two realizations (“yes” or “no”, i.e. simultaneous failure or not of another essential plane sub-system). The data can be obtained from airline statistics about the performance of relevant sub-systems during the different flight phases.

10. **Flight outcome.** This deterministic variable has three realizations: “success”, “severe shaking” and “accident”. “Severe shaking” represents an outcome that includes injuries to passengers and/or damage to the aircraft, but without casualties. The variable is conditioned on: “Altitude”, “Simultaneous Failure”, “Weather”, “Pilot’s Action”, and “Timing of Signals”.

The deterministic function linking flight outcome to these variables has to be determined by airline experts. For example, if an LE problem occurs at low altitude and the pilot’s reaction is inappropriate, an accident occurs.

**References**