

# ASSESSMENT OF THE COST OF OPERATIONAL CONSEQUENCES OF FAILURES IN AIRCRAFT OPERATION

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## Abstract

Maintenance decisions regarding aircraft require consideration of the operational impact of failures. The cost of the operational impact of failure is difficult to assess due to the influence of a large number of contributory factors. This study attempts to assess the cost of operational consequences of failures using the expertise of the field experts following a pairwise contribution technique. The study shows that the proposed model can be a tool to assess the cost of operational consequences of failures in aircraft operation, when there is not sufficient and reliable data.

Keywords: Operational impact, Failure consequence, Cost of delay, Pairwise comparison.

## 1. INTRODUCTION

An airline must ensure the safety and optimum service reliability of its fleets. This could be achieved by minimizing the intrusion of sudden technical failures and unplanned downtime leading to operational irregularities and interruptions in an aircraft's regular operation.

One way of mitigating or eliminating the effect of sudden failure is to cope with the failure process proactively, e.g. by performing scheduled maintenance. The maintenance task related to any failure with operational consequences is economically acceptable only if, over a period of time, the cost of preventive maintenance would be less than the combined cost of the operational consequences of failure and the related cost of corrective maintenance [1].

Therefore, preventive maintenance may be a viable alternative only if it is cost effective, i.e. the total cost of corrective maintenance including the cost of expected operational consequences of the failures and the cost of associated corrective maintenance task exceeds the cost of the proposed preventive maintenance task.

Failures with operational consequences may cause different operational interruptions that can be primarily divided into two main groups, i.e. ground or air interruptions [2]. All of these events result in direct financial losses, such as additional costs related to the flight crew, ramp and airport, the aircraft itself, passengers, and might lead to loss of revenue if the failure effect leads to flight cancellation.

These consequences may also result in some indirect financial losses, due to customer dissatisfaction, passenger ill-will, and loss of opportunity. All of the mentioned consequences involve revenue losses in addition to the cost of corrective maintenance. Most airlines recognize that the operational cost of a delayed aircraft is greater than the normal operating cost primarily due to extra costs incurred for crew, passengers, aircraft, and ramp. This extra cost serves as a measure of the economical aspect of failure effect on operation.

Exact quantification and assessment of the cost of operational consequences of failures is a challenge due to a long list of contributory factors, e.g. inadequacy in required information/data and lack in understanding regarding their nature of influence. However, the experience of field experts may provide an effective database towards this estimation.

This paper focuses on the study of the operational consequences of failures which lead to delay. In order to effectively utilize the knowledge of field experts in the assessment process, a pairwise comparison technique was adopted for quantifying the contribution of different factors to the operational cost of a delayed aircraft.

## 2. MODE, TYPE AND CONSEQUENCES OF FAILURES

Depending on the nature and state of a failure, it may be detected by the crew or remain undetectable. Hence, failures are broadly classified into two groups, i.e. evident and hidden failures. By definition, failure modes that are evident to the crew are termed evident failure and conversely failure modes not evident to the crew are known as hidden failures [3, 4].

Follow-up actions for failures depend on which mode they belong to i.e., whether the failures are evident or hidden to the operating crew. In respect to the type of failure, the user also is concerned about its impact on safety, operations, and economics as detailed in the following section [5]:

- Evident safety– Includes evident failures that produce an immediate adverse effect on safety.
- Evident operational– Includes evident failures that produce adverse effects on operations.
- Evident economic– Includes evident failures that produce adverse effects on economics.
- Hidden safety – Includes hidden failures that produce an adverse effect on safety.
- Hidden non safety–Includes hidden failures that produce adverse effects on operations and/or economics.

Figure I details a failure classification on the basis of extent and time of “failure consequence”. An evident failure may have immediate impact on the aircraft’s regular operation, but hidden failures have no immediate effect on operation as their consequences are delayed.

Based on the definition, failure modes having safety consequences involve possible loss of the equipment and its occupants. Failure modes having operational consequences, involve indirect financial losses due to operational irregularities and direct cost of repair, and the failure modes having economic consequences involve the direct cost of repair only. [3]

Correction of failures, immediate or deferred, consumes time, human resources, and material. Hence all failures have financial consequences. Failures of aircraft that cannot be repaired within the available time (transit time) have operational consequences mainly due to delay to the next flight operation.

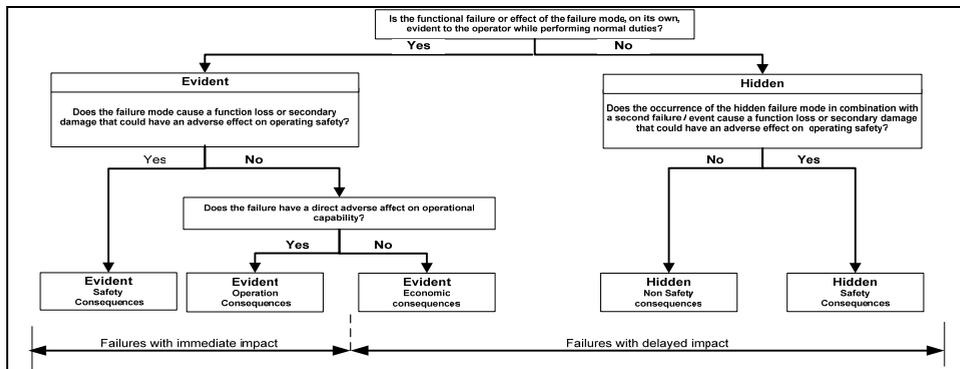


Figure. I: Classification of failures

### 3. MAINTENANCE SELECTION AND FAILURE CONSEQUENCE

Ideally the role of Preventive Maintenance (PM) is to cope with the failure process proactively and to ensure a safe and reliable operation of the aircraft at the lowest possible cost. PM reduces the problems associated with the occurrence of sudden failures so as to eliminate waste and to reduce aircraft Life Cycle Costs (LCC). In general, the aim of any PM schedule is to prevent failure, to detect the onset of the failure or to detect hidden failure [6]. Complete failure prevention might not always be feasible and then PM aims at the reduction of failure probability to an acceptable level or to mitigate the consequences of failure.

In order to develop initial scheduled maintenance tasks, Reliability-Centered Maintenance (RCM) and consequently, MSG-3 (Maintenance Steering Group methodology) have been introduced. RCM and MSG-3 are well-structured logical decision processes, used to identify the policies that must be implemented to manage the different failure modes causing functional failure in a given operating context. These methodologies rank the criticality of failure modes and provide guidelines for the selection of appropriate PM tasks that are most effective in preserving system function. [7, 3]

RCM and MSG-3 recognize that the consequences of failure are the key to all maintenance decisions rather than the failure itself. So the emphasis in any maintenance action lies on the avoidance or reduction of the consequences of failures to an acceptable level [7, 3], not on the avoidance of failures per se. Therefore, the consequences of failure determine the priority of the maintenance activities or design improvement required to prevent its consequences [3]. Following this concept, it is possible to identify the maintenance objectives more explicitly and consequently to devise the best possible way to rectify the problems.

Regardless of the methodology that one follows to frame a maintenance program, the prime concern is whether, the selected maintenance task is fulfilling its objectives or not. Therefore, maintenance task selection needs to have overriding criteria to recognize the fulfillment of these objectives. Selected maintenance tasks must satisfy the requirements of the type of failure to restore its initial performance and capability, i.e. a maintenance task is employed only when it eliminates a failure or reduces the probability of its occurrence to an acceptable level or reduces the impact of failure [4].

According to MIL-STD-2173, effectiveness is a measure of the result of the task objectives in terms of the failure consequences. Therefore, after choosing an applicable task, the effectiveness of the task in preventing the failure consequences must be determined.

Financial consideration is a must in maintenance task selection as the contribution of any activity to a business is measured ultimately in financial terms. According to the RCM and MSG-3 methodologies, if the failure does not involve safety, the task must be cost effective, i.e. the cost of a proposed applicable maintenance task should be less than the cost of prevented apprehensive failures.

Hence, the analysis of cost effectiveness of a PM task warrants the estimation of both the imputed cost assigned to the proposed PM task and expected operational consequence of the failure. Only then it is possible to compare both costs and find the most cost-effective task to chose.

#### **4. ASSESSMENT OF OPERATIONAL CONSEQUENCES OF FAILURES**

Failure modes interfering with the completion of the aircraft mission are known as failures with operational consequences [5]. In other words, a corrective action to a failure that disrupts planned flight operations is classified as an operational consequence. These failures cause various operational interruptions that may be divided into two main categories [2]:

- Ground interruption
- Air interruption

Ground interruption includes delay in flight dispatch, ground turn back, aborted take off, aircraft substitution, and flight cancellation. Air interruption includes in-flight turn back, diversion, go around, touch and go, and re-routing, or some operational restriction such as altitude restriction.

Three approaches have been developed in the aviation industry to manage operational interruptions and minimize the technical delays of possible failures [8, 9]:

- Redundancy
- Modular design and Line Replacement Units (LRU)
- Identifying minimum aircraft dispatch requirements stated in Minimum Equipment List (MEL).

Item redundancy is a common engineering solution for the problems associated with high degree of reliability requirement. If one unit fails, the standby unit is available to take over the function. LRUs are those items that can be quickly removed and replaced so that, the aircraft can returns into service without any technical delay [9]. MEL also allows the aircraft to continue its service with certain items inoperative provided the loss of function does not affect the safety and operational capability of the flight.

Based on the gravity of the situation, the adverse effects of a failure on operating capability may require any one of the following actions [10]:

- Correction of the failure prior to further dispatch.
- The imposition of operating restrictions.
- Flight crew uses abnormal or emergency procedure.

The assessment of whether or not a failure meets one of the above-mentioned criteria requires reference to the Minimum Equipment List (MEL), Flight Manual (FM), Flight Crew Operation Manual (FCOM), Quick Reference Handbook (QRH), the pilot's experience and technical limitations and allowances. As an example, MEL document give some relevant information on how long the aircraft can fly with an item inoperative and what necessary actions must be taken to permit the aircraft to remain in service.

The magnitude of the operational consequences of a particular failure mode mostly depends on the type and nature of the failure, phase of flight operation i.e. when the failure occurs (e.g. prior to dispatch, taxi, take off, climb, cruise, decent, approach, and landing) and the expected time duration for the rectification of the failure (less than 15 minute, more than one hour, etc.). Depending on the occurrence of the above mentioned factors, different scenarios for operational consequences might arise. For instance, if a non-deferrable failure happens in climb, and the final decision is diversion to the base airport, the flight will introduce airborne delay cost due to preparation to divert, and a ground delay cost due to the additional ground time needed for failure rectification.

In general, the operational consequences of any failure finally influence the profit and loss of the airlines directly or indirectly.

It has to be mentioned that failures that require immediate correction do not necessarily have operational consequences. For example, if a failed item on an aircraft can be replaced or repaired during the normal transit time, at a line station, then it causes no delay or cancellation of subsequent flights and the only economical consequence is the cost of corrective maintenance. In contrast, the aircraft may be operational with certain types of failures, but its operational capability might be reduced, resulting in increased operating cost due to high fuel consumption, longer flight time etc.

However, in all cases, the total cost of an operational failure includes the economic loss resulting from the failure as well as the cost of correcting it. If a failure has no operational consequences, the cost of corrective maintenance is still incurred and is the only cost. The cost of operational consequence of a failure also depends on the size and type of the aircraft, the management policy of the operating airline and its maintenance support system. Therefore, the magnitude of operational consequences will vary from one operating context to another. Hence, developing a universal model for assessing the cost of operational consequence of failure is difficult.

In the following section, we shall discuss a specific hypothetical case where failure appears prior to dispatch and corrective action is required to rectify the failure prior to further dispatch leading to flight delay.

## **5. PROPOSED METHODOLOGY**

Maintenance actions consume time and resources and have direct financial impact. A delay occurs if the time needed for maintenance plus the time elapsed before maintenance starts is longer than the layover [11]. In fact, maintenance which lasts more than the planned available time causes a delay also to the next schedule of the aircraft, which results in direct or indirect financial losses for the airlines. These losses are mainly due to the cost of delay in operation and are considered in this study as financial aspect of delay due to technical failure.

For the most part airlines recognize that crew, ramp, aircraft and passenger related costs, contribute the lion's share to their respective delay costs [2]. Therefore, we have split up delay costs into the above four cost headings.

The profit and loss account reflects the economic status of any business. A business makes profit when the collected revenue exceeds the related expenses and there are two parts to this for any airline: (a) planned expenses and (b) unplanned expenses. The cost of the operational consequences of failure falls into the category of unplanned expenses.

In this paper, the cost of technical delays (as a consequence of aircraft technical failure) has been expressed in percentage of the crew-related planned operation expenses. An effort was made to find the contribution of different cost headings towards the delay cost from the judgments of experts following a pairwise comparison technique. This technique was originally suggested by T. L. Saaty (1980) and has played an important role in the decision making process for engineering, business and management.

In this study the experts were asked to judge the relative contribution of two delay cost headings that form the judgment matrix regarding the contribution of the different cost headings into the cost of operational delay.

Out of the above four delay cost headings, crew related expenses are mainly the predetermined overtime paid due to delay, and are almost fixed as a percentage of planned crew related cost. Therefore, by calculating the overtime paid to the crew, the remaining three delay costs headings could be calculated with the help of values of contribution matrix. In the following section, the algorithm for the proposed model is discussed.

### **5.1. Algorithm for the proposed methodology**

Step 1: Collect information from the airline regarding the planned operational expenses per flight hour and the maximum profit per flight hour, when there are no operational irregularities and a normal situation prevails. The operational impact is lowest or negligible in this case. Express maximum profit in percentage of planned operational expenses. Also, collect data from the airline regarding the maximum loss per flight hour for the highest operational irregularities in the worst scenario. Here, the operational impact is the highest and the cost of operation impact overrides the profit margin. The operation of the flight become uneconomical and the business runs at a loss. Express maximum loss in percentage of planned operational expenses. A typical example of the operational impact of failure on the economy of the organization is explained in Figure II.

Step 2: Calculate the range of the cost of operational impact in percentage of planned expenses using the information from Step 1. Divide the range into the term set of operation impact such as, negligible, very low, low, moderate, high, very high.

Step 3: Select a group of experts from the operating airlines and collect their opinion of pairwise comparison regarding the contribution of the four cost headings towards delay cost with varying size and type of the aircraft as well as delay duration.

Step 4: Calculate and rank the priority values of different cost headings following the responses of the experts as exhibited in their respective pairwise comparison matrices. The experts are asked to modify their judgments whenever the consistency ratio exceeds the acceptable range of 10%.

Step 5: Calculate the crew related delay cost using the information collected in Step 1.

Step 6: Calculate the delay cost using the priority matrix values of Step 4 and sum up all the delay costs to estimate the total delay cost and determine where it falls in the linguistic term set developed at Step 2. This will guide management in framing an appropriate maintenance policy.

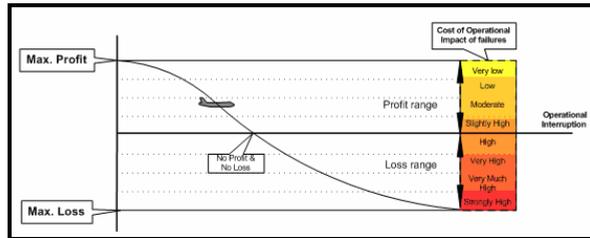


Figure.II: A typical qualitative example of effect of delay on economy.

### 5.2. Pairwise comparison matrix

It is hard to expect a reasonable numerical value for the percentage contribution of each of the four cost headings into the total delay cost from experts as they are influenced by a large number of factors. Many of these factors are subjective in nature. However, it is comparatively easier to compare the relative importance of two factors at a time, as is done in the pairwise comparison approach pioneered by Saaty (1980). This approach is based on the fundamental principle that it is more difficult to evaluate  $n$  elements (where  $n > 2$ ) simultaneously than to compare two such elements at a time. In pairwise comparison experts compare the importance of two factors on a relatively subjective scale. In this way a judgment matrix of importance is build up according to the relative importance given by the experts. Table I represents a pairwise comparison scale for value rating of judgements and for deriving pairwise ratio scales. Table I includes reciprocals, which are equally often adopted for relative measurements or comparisons of factors. A total of  $\frac{n(n-1)}{2}$  judgements are required for comparing  $n$  factors.

Table I Pairwise comparison scale

	Verbal judgement
1	Elements are equally preferred
3 or (1/3)	One is moderately preferred to the other
5 or (1/5)	One is strongly preferred to the other
7 or (1/7)	One is very strongly preferred to the other
9 or (1/9)	One is extremely preferred to the other
Note: (2, 4, 6, 8: intermediate judgemental values between adjacent scale values)	

## 6. METHOD OF COLLECTION OF JUDGEMENTS FROM DIFFERENT EXPERTS

To perform the pairwise comparison, a suitable team of experts at different positions in the organization are invited. We suggest that level of experience is a major factor when choosing the respondents. A multiple choice questionnaire consisting of six questions regarding the relative importance of one cost heading over the other to

the total delay cost, as shown in a sample questionnaire in appendix A was prepared. Three field experts were chosen and were asked to mark their opinion on the multiple choice response sheets for a delay less than 15 minutes.

### 6.1. Measuring inconsistency in judgements

Human judgements are the basis of the pairwise comparison approach. Some degree of inconsistency may be introduced in pairwise comparisons as a result of a number of factors, such as:

- lack of adequate information;
- improper conceptualisation;
- mental fatigue.

The difference  $\lambda_{\max} - n$ , (where,  $\lambda_{\max}$  is the largest eigen value and  $n$  is the number of comparisons) can be employed as a measure of inconsistency. For perfect consistency the difference ( $\lambda_{\max} - n$ ) will be zero. But instead of using this directly, Saaty (1980), defined a Consistency Index (CI) calculated as:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (1)$$

The closer this CI is to zero, the better the overall consistency in the judgements.

Simulation of a large number of randomly generated pairwise comparisons for different sizes of matrices carried out by Saaty, with regard to calculations of the average CIs, resulted in what he defines as the Random Index (RI). The values of such standard CIs (or RIs) are presented in Table II [12]. The significance of the values of RI is that the ratio of the CI for a particular set of judgements to the RI of the same size of matrix (such as given in Table II) indicates a measure of the inconsistency ratio or consistency ratio (CR) for the matrix of judgements, i.e. a measure of inconsistency in judgements. A perfectly consistent judgement will yield a CI of zero (0), the CR will also be zero. Usually, a value of CR between 0 and 0.10 (i.e. 10 percent of what would be the outcome from random judgements) is acceptable [13]. If the obtained value of RI is not within an acceptable range, the experts may be asked to modify their judgements in the hope of getting a modified consistent matrix.

The CR of the judgement matrices of all the experts was calculated. Depending on the value of the CR some experts were asked to modify their judgements. The final judgement of the three experts are presented in Appendix B and the CR values of their judgement matrices for delays less than 15 minutes are tabulated in Table III.

### 6.2. Aggregating judgements of different experts

Each expert generates their pairwise comparison matrix for the set cost headings. As pointed out by Aczel et al, (1983), the same pairwise comparison for each expert can be aggregated into a group comparison by taking the geometric mean of all comparisons. The geometric mean is the only averaging process that maintains the reciprocal relationship ( $a_{ij} = \frac{1}{a_{ji}}$ ) in the aggregate matrix. The general formula for calculating a geometric mean for a group response is:

$$\text{Weighted mean value of } a_{ij}: \quad a_{ij} = \left( \prod_{k=1}^n w_k \bullet a_{ij} \right)^{\frac{1}{\sum_{k=1}^n w_k}} \quad (2)$$

Where  $a_{ij}$  is each expert's paired comparison value,  $n$  is the number of expert, and  $w_k$  is the weight of the  $k^{\text{th}}$  expert. In this study we have assumed that all the experts have equal expertise in their judgements and therefore  $w_k = 1$  for all  $k$ . The individual and overall judgement matrixes are given in Appendix B. The contribution of the four cost headings to the total cost of delay is given in Table IV, the priority vector of the pairwise comparison matrix.

Table II: RI of many randomly generated pairwise comparison matrices of size n

Size of matrix (n)	Random index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Table III: Final CR values of the judgement matrices for delays less than 15 min

Expert	CR value
No. 1	0.01
No. 2	0.0037
No. 3	0.0175
Aggregate	0.0002

## 7. RESULTS AND DISCUSSION

To illustrate the application of the proposed model, a hypothetical single-aisle, twin-engine and short range aircraft has been selected, and the opinions of the field experts were collected and aggregated (see Appendix B). The results given in Table IV show that for a delay up to 15 minutes the extra cost incurred for the passenger is the maximum and is more than the half of the total cost of delay in this hypothetical case. The additional cost for the overtime of crews amounted to almost one third while the extra cost for ramp is only 10.8%. Additional cost for operation of aircraft contributes the least to the total cost of delay. The financial effect of delay is explained in Figure II. This clearly shows the financial impact of delay categorically helps management in decision making. Table IV lists the contributions of the four delay cost headings with their amount of contribution in percentage of cost of operation. The basis of these calculations is:

- The cost of operation per flight hour = 3500.0 €.
- Maximum profit = 525.0 €.
- Maximum loss = 7000.0 €.
- Cost of crew overtime per hour = 517.0 €.

The calculated value of total cost of delay is 26.46 € per minute, which is 45.36% of the cost of operation.

Table IV: The contribution of the delay's four cost headings

Cost Heads	Contribution to total cost of delay	Cost per minute of delay
Aircraft related cost	5.96%	1.58 €
Ramp related cost	10.81%	2.86 €
Crew related cost	32.56%	8.62 €
Passenger related cost	50.67%	13.41 €
Total	100.00%	26.46 €

## 8. CONCLUSIONS

This study shows a methodology of calculation of the cost of delay using the expertise of field experts when there is no available or reliable data. This methodology can excel in the estimation of the cost of delay provided there is access to a good number of experts with a sound experience of the company's economy and maintenance issues. This methodology can help the management of operating airlines to frame their maintenance policy by providing useful data regarding the cost of delay due to maintenance. The applicability of the methodology is universal for the type and size of the aircraft and the duration and type of delay.

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