EFFECTS OF CONDITION-BASED MAINTENACE ON COSTS CAUSED BY UNSCHEDULED MAINTENANCE OF AIRCRAFT

Structured Abstract

Purpose

This paper analyses the effects of condition-based maintenance based on unscheduled maintenance delays that were caused by ATA chapter 21 (air conditioning). The goal is to show the introduction of condition monitoring in aircraft systems.

Design/methodology/approach

The research was done using the Airbus In-Service database to analyse the delay causes, delay length and to check if they are easy to detect via condition monitoring or not. These results were then combined with delay costs.

Findings

Analysis shows that about 80% of the maintenance actions that cause departure delays can be prevented when additional sensors are introduced. With already existing sensors it is possible to avoid about 20% of the delay causing maintenance actions.

Research limitations/implications

The research is limited on the data of the Airbus In-Service Database and on ATA chapter 21 (air conditioning).

Practical implications

The research shows that delays can be prevented by using existing sensors in the air-conditioning system for condition monitoring. More delays can be prevented by installing new sensors.

Originality/value

The research focuses on the effect of the air-conditioning system of an aircraft on the delay effects and the impact of condition monitoring on delays.

INTRODUCTION

This section will introduce the reader to the concepts and specifics of aircraft environment. It will show what the goals of aircraft maintenance are and what regulations apply.

1.1 Aircraft Maintenance

Aircraft maintenance is based on Reliability Centred Maintenance. The goal is to have maximum safety and reliability with minimization of costs. Tasks are selected in a hierarchy of difficulty and cost, from lowest to highest. Each task must also pass the applicability and effectiveness criteria. Depending on the consequence of failure (safety, operational, economic, hidden safety and hidden non-safety) a single or combination of tasks is selected (Nowlan & Heap, 1978)

Reliability is the probability that an item will perform its intended function for a specified interval under stated conditions (US Department of Defense, 1998).

For this purpose the Maintenance Steering Group (MSG) was formed and they developed different maintenance concepts for aircraft. The most resent is MSG-3 (Federal Aviation Administration, 2012). Focus of MSG-3 is the effect of a failure on the aircraft operation (Nowlan & Heap, 1978) (Air Transport Association of America, 2007). This means that for each item that effects the airworthiness a specific maintenance task is described (task oriented maintenance). MSG-3 can use condition based maintenance or predetermined maintenance to achieve its goals. Predetermined maintenance is used by most airlines and manufacturers. Preventive maintenance with scheduled provides a benefit not only for the economical aspect but also for reliability (Kiyak, 2012).

The core concept of MSG-3 is the Failure-Mode-and-Effect-Analysis (FMEA). With FMEA it is possible to determine which maintenance actions need to be performed during planned maintenance. This includes taking the probability and effects of a failure into account and planning the maintenance during system development. The FMEA uses a top-down approach where the analysis is started at highest system level. This approach does have the advantage that a lot detail analysis is not needed, because most maintenance tasks are found at higher levels.

The FMEA process does have the following steps (Society of Automotive Engineers, 2001):

Identify Relevant Functions In this step are all functions of a system identified. See Table 1 for an example of a function.

Identify Functional Failures The next step is to define the functional failure of a function. A function can have multiple failure modes. See Table 1 for an example.

Identify Failure Effects The failure is classified by the effect using the process in Table 1

Identify Failure Probability The probability of a failure is then calculated based on experience or in-service data.

Select Maintenance Tasks It is possible to define maintenance actions to prevent a failure, when the causes of a failure are defined. This step also includes determining the maintenance intervals, combining maintenance tasks and remove duplicate tasks.

Function	Functional Failure	Failure Mode
Provide redundant capability of informing crew of fire in each of the four specific areas (right hand Fan, left hand Fan, Core upper case, Core lower case) in case of fire.	Loss of redundancy to detect fire in the designated engine fire zone.	Engine fire detector failure.
	Provides false fire warning indication.	Engine fire detector failure.
Alerts crew of detection loop failure.	Does not alert crew detection loop failure.	Engine fire detector failure.
		MAU Failure.

Table 1 - Example Functional Failure Analysis - Engine Fire Detection System (European Aviation Safety Agency, 2005)

Failure Classes
Failures are classified into five classes to determine the effect of a failure on the aircraft. A criterion for the classification is the severity of the failure for the aircraft safety. The Table 2 shows how failures are classified.

<table>
<tr><td colspan="5">Is the occurrence of a functional failure evident to the operating crew during the performance of normal duties?</td></tr>
<tr><td colspan="3">Yes</td><td colspan="2">No</td></tr>
<tr><td colspan="3">Does the functional failure or secondary damage resulting from the functional failure have a direct adverse effect on operating safety?</td><td colspan="2">Does the combination of a hidden functional failure and one additional failure of a system related or backup function have an adverse effect on operating safety?</td></tr>
<tr><td>Yes</td><td colspan="2">No</td><td>Yes</td><td>No</td></tr>
<tr><td></td><td colspan="2">Does the functional failure have a direct adverse effect on operating capability?</td><td></td><td></td></tr>
<tr><td></td><td>Yes</td><td>No</td><td></td><td></td></tr>
<tr><td>Safety</td><td>Operational</td><td>Economic</td><td>Safety</td><td>Non Safety</td></tr>
<tr><td colspan="3">Evident</td><td colspan="2">Hidden</td></tr>
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Table 2- Failure classes criteria

This results in the following failure classes (Air Transport Association of America, 2007):

Evident Safety This must be approached with the understanding that a task is required to assure safe operation. If this is not the case then a re-design is required.

Evident Operational A task(s) is desirable if it reduces the risk of failure to an acceptable level.

Evident Economic A task(s) is desirable if the cost of the task is less than the cost of repair.

Hidden Safety A task(s) is required to assure the availability, necessary to avoid the safety effect of multiple failures. If this is not the case then a re-design is required.

Hidden Non Safety A task(s) may be desirable to assure the availability necessary to avoid the economic effects of multiple failures.

Failure Probability
Ideally in-service data is used to evaluate the risk of a failure based on the different parts. However normally during the development, no in-service data is available. This means that during development assumptions need to be taken based on similar parts, tests, simulations or experience. Later when in-service data is available it can be used to update the failure probability.

Failure class and failure probability define the criticality of the failure. The criticality is used to plan the maintenance action.

1.2 Scheduled Maintenance

Periodic maintenance actions are organised in five different classes of checks. Each check is performed at a different interval and gets more complex with the size of the interval. The given intervals can vary depending on the aircraft type and aircraft operation (Air Transport Association of America, 2007).

Pre-/Post Flight Check
The most performed maintenance check is the pre-/post flight check that is done on a daily basis. This check is often done by the pilot by walking around the aircraft and checking the general state of the aircraft.

A-Check
A-checks can be performed overnight in an hangar and are done every two month. During an A-check all technical systems that are needed for aircraft operation are checked.

C-Check
The C-check is a major aircraft check, where the aircraft is taken out of operation to be inspected. C-checks every two years and take about two weeks. The aircraft structure is inspected and all systems are tested.

IL-Check
The IL check is done every four years and includes a detailed checking and maintenance of systems and structure.

D-Check
This check is done every ten years and takes about one month of work. During this check nearly the whole aircraft is dissembled and checked. Sometimes the paint is removed to check the structure. An aircraft does have two to three D-checks during its life time.

1.3 Maintenance Program Development

The process to develop a maintenance plan for scheduled maintenance based on the MSG-3 method is complex. An Industry Steering Committee (ISC) consisting of authorities, aircraft operators and manufacturer is created. These actors form groups (MSG Working Groups (MWGs)) which frequently meet and decide on the frequency and scope of needed maintenance actions (see Figure 1). First the MSG-3 analysis is performed based on aircraft data. Then a Maintenance Review Board Report (MRBR) proposal is created, which then needs to be accepted. The MRBR contains the minimum scheduled tasking/interval requirements for a newly FAA type-certificated (TC) or derivative aircraft and its aircraft engines. The accepted MRBR is then used by the manufacturer to create the Maintenance Planning Document (MPD) (Federal Aviation Administration, 2012) (Federal Aviation Administration, 1994) (European Aviation Safety Agency, 2008).

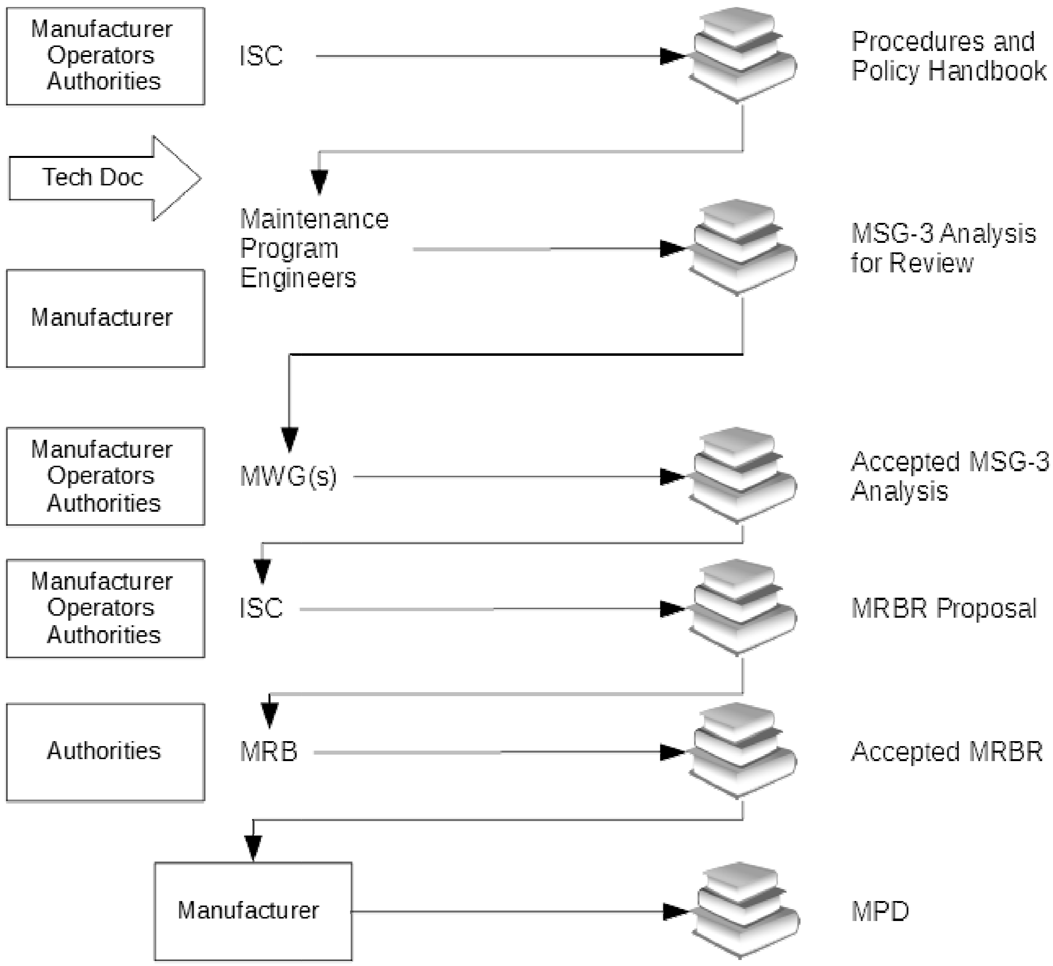

Figure 1 - MRBR Process

Revisions requiring formal approval will be subject to the same consideration as initial approval (Federal Aviation Administration, 1978). That means that changing the maintenance plan is a difficult process that requires good reasons the change the maintenance intervals. European Aviation Safety Agency (2008) defined a process how to update maintenance intervals. This process is needed because initially no in-service data for a new aircraft is known and the maintenance intervals are created based on estimations. Operator in-service data is needed to adapt the maintenance intervals.
Ali and McLoughlin (2012) showed how much costs can be saved by optimizing the maintenance intervals.

1.4 Unscheduled maintenance

Unscheduled maintenance is maintained that needs to be done outside of the defined periodic intervals because an unexpected failure occurred. The aircraft continues to fly safely due to its built-in redundancy, but the equipment (generally) needs to be fixed before the next take off. If it is not possible to fix the equipment during turnaround time, the flight will be delayed until the fault is eliminated. Depending on the failure it is possible that the aircraft needs to stay on ground until the failure is fixed. If the aircraft needs to stay on ground (AoG - Aircraft on Ground) depends on the Minimum Equipment List (MEL) (International Civil Aviation

Organization, 2015) (Civil Aviation Regulations Directorate, 2006). The MEL is based on the Master Minimum Equipment List (MMEL) (International Civil Aviation Organization, 2015) (Civil Aviation Regulations Directorate, 2006) that is accepted by national airworthiness authorities. The MEL is an operator defined list that is stricter than the MMEL. Both lists contain items that are not needed for the aircraft operation. If a faulty part is not in the MEL then the aircraft is not allowed to operate until the failure is fixed.

Depending on the flight schedule of the aircraft it is possible that a departure delay may occur because of the maintenance operation. In addition to having a delay it is possible that the flight needs to be completely cancelled. Delays and cancellations are very expensive for an airline (Cook, et al., 2004) and shall be avoided if possible.

1.5 Preventive Maintenance

Preventive maintenance (PM) is the standard method for reducing unscheduled maintenance. Aircraft components are inspected after given time intervals. The intervals depend on the component type and can vary from airline to airline. Reducing the time interval can increase the need for spare parts; increasing the interval increases the risk of unscheduled maintenance (Kolerus & Wassermann, 2011). Looking at preventive maintenance in more detail, three types can be identified (Air Transport Association of America, 2007) (Nowlan & Heap, 1978) (Civil Aviation Authority, 1995) (Federal Aviation Administration, 1978):

Hard-Time (HT): Scheduled removal of a component before some specified maximum permissible age limit.

On-Condition (OC): Scheduled inspections, tests, or measurements to determine whether an item is in, and will remain in, a satisfactory condition until the next scheduled inspection, test, or measurement.

No Maintenance: This approach assumes that the component can be used until it breaks and it is then replaced. In MSG-2 this maintenance process was called "Condition Monitoring". This maintenance process is no preventive maintenance process, but a corrective (reactive) maintenance process, however it is used for certain components in aircraft maintenance.

1.6 Condition-Based Maintenance

Condition-based maintenance (CBM) is based on condition monitoring and aims at preforming maintenance based on the system condition and trend of the system condition. CBM can be used as a way to realize RCM (Niu & Pecht, 2009).

Condition monitoring constantly measures and analyses relevant mechanical and electrical component parameters during operation. Those parameters are selected for monitoring that allows determining the condition and failure state. The need for maintenance of the component is only indicated, if parameters show a predefined degradation of the component (Kolerus & Wassermann, 2011).

The difference between CBM and preventive on-condition maintenance is, that OC checks a system at defined intervals while condition monitoring continuously monitors the condition.

Condition Monitoring is used in a wide field of applications. Common fields of applications are rotary machines (gear boxes, gas and wind turbines, bearing … (Mahamad, et al., 2010) (Saravanan & Ramachandran, 2009) (Sugumaran & Ramachandran, 2011) (Tian & Zuo,

2010) (Zhao, et al., 2009), plants and structures (bridges, pipelines … (Goode, et al., 2000)). Often vibration data is used to perform the condition monitoring (Ebersbach & Peng, 2008).

The condition of the system is then defined by setting limits on certain values from experience condition (Mobley, 2002) or based on a mathematical or data driven model (Kolerus & Wassermann, 2011) (Williams, et al., 1994). Often are also machine learning techniques (decision trees (Sugumaran & Ramachandran, 2007) (Sugumaran & Ramachandran, 2011) (Tran, et al., 2009), vector support machines (Pham, et al., 2012) (Sugumaran, et al., 2007) (Widodo & Yang, 2007), neural networks (Chen, et al., 2012) (Mahamad, et al., 2010) (Tian, 2012) used to map the features of the input signal to a condition.

Another option is to use a mathematical model and feed the sensor input to the model and calculate the output and check how the output of the theoretical model deviates from the real system. This approach can also be used for fault isolation and fault identification of failures in addition to prognosis (Wang, et al., 2008) (Williams, et al., 1994) (Kolerus & Wassermann, 2011) (Jardine, et al., 2006).

Data-driven-models use past data to create models with stochastically or machine learning algorithms (Pecht, 2008) (Garcia, et al., 2006) (Jardine, et al., 2006). These models require many data samples that represent different condition of the system. Data-driven-models require less man-power than a mathematical model; model validation and testing can be performed almost automatically.

Trend analysis is method to achieve CBM. The analysis algorithm does not only look at recorded parameters at a single moment in time, but rather takes the full parameter history into account. The need for maintenance of the component is only indicated, if the data trend of parameters shows a degradation of the component. Based on the parameter time history, the analysis algorithm also allows giving a forecast of the remaining lifetime of the component (Kolerus & Wassermann, 2011). Analysis and prediction can use a variety of methods for predicting future values. ARMA, ARIMA, artificial neural-networks, sequential Monte Carlo and Markov models are used for prediction values for a complex time series (Chen, et al., 2011) (Caesarendra, et al., 2010) (Pham & Yang, 2010) (Tian, et al., 2010). Output of the prediction is normally an estimated time to failure (ETTF) and a confidence interval (Sikorska, et al., 2011). The confidence interval defines how reliable a prediction is (Schruben, 1983) (Sikorska, et al., 2011). The confidence interval can be calculated by using standard time series.

Implementing CBM is a difficult and costly task. Many barriers prevent using CBM on a large number of systems. These barriers include (among others) (Stecki, et al., 2014):

- The inability to accurately and reliably predict the remaining useful life of a machine (*prognostics)*
- The inability to continually monitor a machine *(sensing)*
- The inability of maintenance systems to learn and identify impending failures and recommend what action should be taken (*reasoning*).
- CBM programs are initiated without full knowledge of how the system can fail
- Widespread research in CBM but it is invariably directed towards specific techniques (better mousetrap symptom)

2 MAINTENANCE COSTS

Hard and soft costs are very common in maintenance. When defining a model of costs, it is necessary to select those that are easily measurable, from which soft indicators, representing an intangible aspect of a much more complex measurement can be extracted. However, soft indicators, such as the cost of not having carried out training or the non-availability of condition monitoring equipment that could have detected an anomalous vibration, are not measurable using a traditional collection of data. Therefore, it is necessary to look for more easily seen hard costs which contribute the required information.

In the first step, the objectives of the system must be properly defined. The costs of a system's maintenance cannot be modeled when the inherent objectives of its design or the operational objectives for which it has been acquired are not known. Thus, for example, in the case of a spare or redundant centrifugal pump, the objective of the system is its condition of redundancy; its maintenance costs will be entirely different from an identical pump used in an area of high criticality due to the vastly different operating conditions.
Once the objectives have been identified, the next step is to select the equipment, if this it has not been already done, and to identify the alternate systems in which it is used. Finally, the optimal configuration for each system is determined, using a method of economic evaluation.
The criteria of evaluation at the time of selecting equipment must balance aspects of both life cycle cost and operational effectiveness. These criteria are shown in Figure 2.

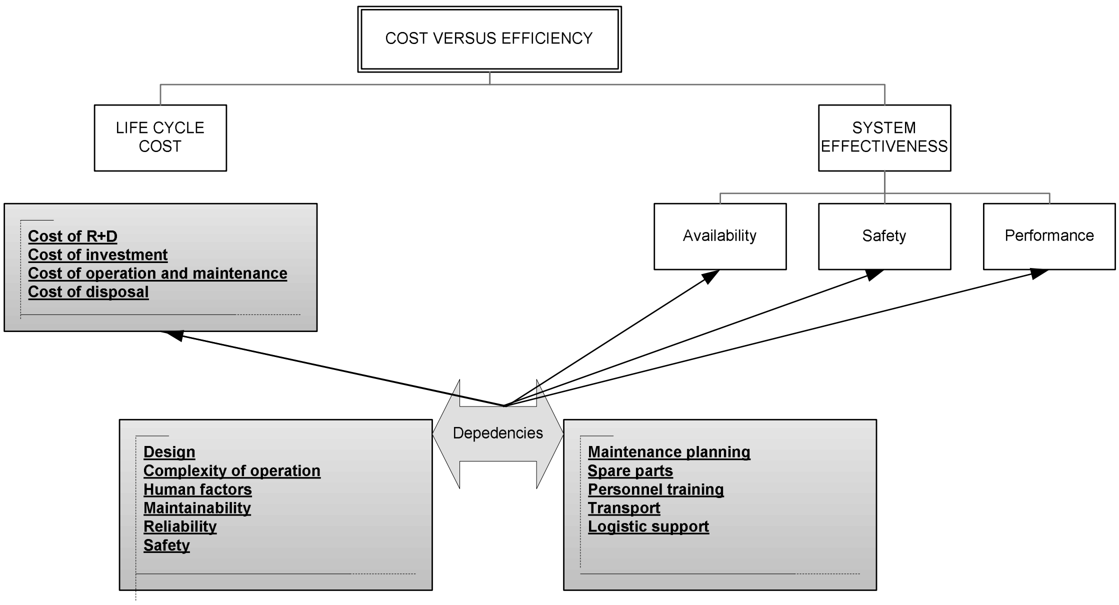

Figure 2 - Effectiveness-cost relationship

A priori, it is less difficult to establish the cost criteria than the criteria of effectiveness using the manufacturer's data or drawing on similar experiences in similar equipment. This does not mean that the estimation of the cost is simple; it only means that normally the various classifications are better understood.
Maintenance costs are an inherent part of life cycle cost (LCC) and cannot be dissociated from the LCC concept. The cost of the maintainability of a system cannot be assessed if it is not considered from its conceptual design stage until its disposal. Therefore, a model of costs must cover the system's entire life cycle; it must include costs associated with research and

development, engineering, design, production, operation, maintenance, and disposal, as shown on the left side of Figure 2.

2.1 Estimation of Maintenance Global Cost

According to (Komonen & Akatemia, 1998), the costs derived from maintenance can be divided into two groups:

- Costs that appear in the operation of maintenance (administrative costs, cost of manpower, cost of material, cost of sub-contracting, cost of storage, cost of capital).
- Loss of production due to shutdowns of production assets or reductions in the production rate, and loss of quality in the product due to equipment malfunctions.

This classification emphasizes the two main objectives of the maintenance function, both corresponding to the desired balance of effectiveness and efficiency:

- High availability of production assets
- Low maintenance costs.

Global cost

According to (AFNOR, 1994) the global cost of maintenance C_g is the sum of four components:

- Cost of interventions (C_i);
- Cost of failures (C_f);
- Cost of storage (C_s);
- Cost of over-investment (C_{oi}).

$$C_g = C_i + C_f + C_s + C_{oi}$$

The objectives of all the facets of the maintenance organization must be aligned so that an attempt to reduce one factor of the global cost will not produce an increase in another factor. The global cost can be calculated for a specific machine, group of machines or whole plants, but policies like RCM that rationalize the observance and application of maintenance only request the calculation of the costs of that equipment whose criticality or economic relevance affects the overall performance of the entire system under consideration. For this reason, the equipment that most affects the global cost will receive more attention and be the subject of more detailed cost analysis.

Recall the problem of the mismatch between overwhelming amounts of data and too little information. For this reason, the data contributed by a cost model to the set of financial indicators will only come from critical equipment or equipment consuming a high percentage of the allocated money (i.e. relevant in the maintenance budget).

2.2 Downtime cost and failure cost

These costs correspond to the loss of profit due to a maintenance problem that has reduced the production rate. They are the result of the following:

- Preventive maintenance badly defined;
- Preventive maintenance badly executed;
- Corrective maintenance performed over an overly long period, badly executed, using bad or low quality spare parts.

It is important to highlight that the cost of failure of the asset corresponds to the loss of profit margin whose cause is a defect that brings losses of production of acceptable quality. The dilemma is whether the cost is attributable to the reasons cited above or to the following:

- Errors of use (misuse) that imply degradation of the asset;
- Environmental conditions outside normal working conditions specified by asset manufacturer.

Such costs must be charged to the production, purchases or even engineering functions, but not to maintenance.
By slotting the costs of failure into the various functional areas, not just into maintenance, those responsible in each area can take corrective measures and in some cases assume full responsibility for the expenses. A single policy which puts all shutdowns and costs of failures under maintenance whatever the reason and no matter who is responsible should not be adopted.
For example, a maintenance failure should not be mistaken with a machine failure caused by buying unreliable equipment. Decisions to purchase or re-engineer equipment almost never depend on the maintenance department but are driven by productivity criteria, making it absurd to transfer that cost to maintenance.
Consider an organization with an engineering department which deploys projects or productive improvements using assets of low reliability, maintainability, safety, etc. without consulting or considering maintenance in any phases of any of the projects. The maintenance department is not involved at all in the decisions and therefore is not responsible for any of the resulting problems. However, as the general perception is that these costs should be attributed to maintenance; there is friction between departments about the imputation of the failure costs, which actually result from making poor decisions at the outset.

2.3 Evaluation of the failure cost

The failure cost can be calculated with the following formula:

C_f = unperceived income + extra production expenses - raw material not used.

The components of this cost are:

- Unperceived income: This factor will depend on the possibility of recovering lost production by rescheduling, working weekends, etc.. In cases of continuous production, however, there is no chance to recover; therefore, the production of that time slot and all incomes which could have been generated during the shutdown must necessarily be imputed to this first part of the equation.

- Extra production expenses: If it is possible to recover part of the production in other temporary slots, the following additional costs will be incurred:
    - Energy required for production;
    - Raw materials;
    - Expendable materials;
    - Services related to quality, purchases, maintenance, etc.
- Unused raw material: When it is not possible to recover production, the cost of the unused raw material will be subtracted from the failure cos. While the raw material has not been used (unless it is a perishable product that must be thrown) it will be consumed if the productive plan is recovered, possibly with some extra storage costs, transport cost or costs related to the degradation of the materials.

The most popular model used to calculate of the cost of failure when there are productive assets that totally or partially assume the tasks of the assets under maintenance is the Vorster method. It is used to calculate the maintenance costs and other financial indicators.

3 DELAYS IN AVIATION

By definition, delays are incurred when an aircraft is prevented from off-block to its destination for an interval of 15 min or more (Federal Aviation Administration, 1995). Delays can originate from traffic, passengers, weather and the aircraft. A delay causes additional operating costs. These costs are crew-related, ramp-related, aircraft-related and passenger-related (hotel and meal, re-booking and re-routing, luggage complaints and revenue losses) (Poubeau, 2002). Delay costs can be calculated from Scholz (1995), Scholz (1998) or Cook et al. (2004).

The average departure delay in 2014 for European air traffic was 26 minutes (Eurocontrol, 2015). 70% and 90% of all flights were not delayed while delays larger than 30 minutes happened in 8% of all departures (Eurocontrol, 2015) (US Department of Transportation, 2014). Flight cancellations are between 1% and 2% (Eurocontrol, 2015) (US Department of Transportation, 2014).

3.1 Delay Causes

The two main reasons for delays were reactionary and airline causes. Reactionary delays are caused by late arrival of aircraft, crew, passengers or load (Eurocontrol, 2015). These delays cannot be controlled because they are caused by an external source. Airline delays include aircraft and ramp handling, technical reasons, flight operation and crewing or passenger and baggage handling (Eurocontrol, 2015). Figure 3 shows the distribution of the delays in minutes per flight; ATFCM stands for “Air Traffic Flow and Capacity Management” and government reasons include security and immigration (Eurocontrol, 2015).

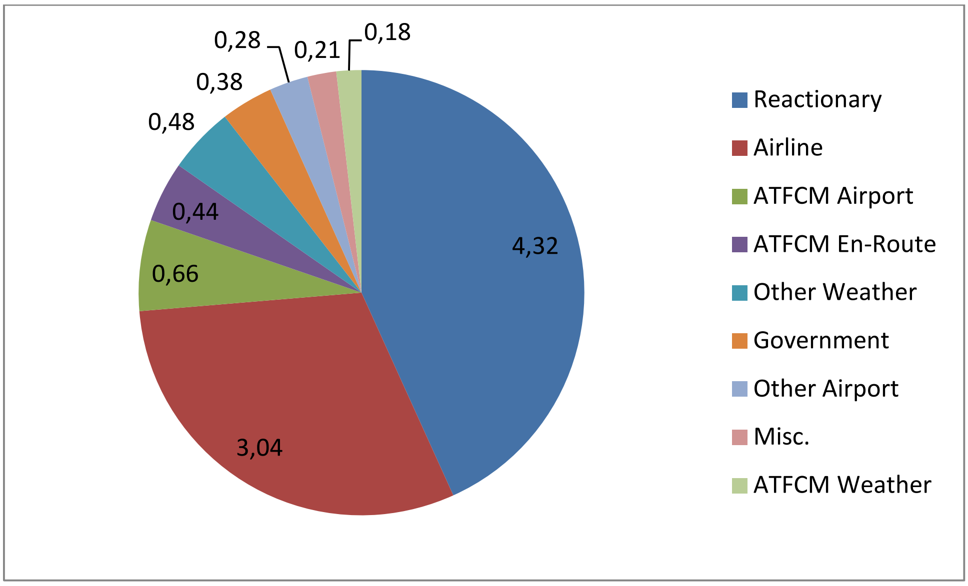

Figure 3 - Causes of departure delays in 2014 in Europe (Eurocontrol, 2015)

Airline delays can be influenced and include delays caused by unscheduled maintenance. IT is difficult to find data sources that show how many percent of the airline causes delays are maintenance delays and to which system caused the problem. However Knotts (1999) shows that about 20% of the delays for the Boeing 747 were caused by technical problems and Civil Aviation Authority (2009) shows how aircraft maintenance is distributed over the aircraft systems. This gives an indication about what systems might cause maintenance delays.

A large problem is delays caused by No Fault Found (NFF) problems, which can make up a significant part of the unscheduled maintenance actions (International Air Transport Association, 2015). The NFF rate for the Generator Control Unit was about 71%.

Airline maintenance policy also affects the number and significance of delays. Rupp et al (2006) shows how an airline policy influences the number of flight cancellations. Flights with fuller aircraft or on routes with higher competition are cancelled less often. It can be assumed that a similar effect can be observed for “normal” delays, because repairs can be deferred according to the MEL. Sachon and Patè-Cornell (2000) analyses how an airline maintenance strategy affects delays, cancellations and safety using a probabilistic risk analysis. The model shows that a marginal trade-off between minimizing delays and maximizing safety for the Leading Edge slat system of an aircraft. Models like this can help to adapt the maintenance policy to reduce delays on a management level of the airline; this includes qualification of maintenance personnel, timing of maintenance operations, number of deferrals allowed.

3.2 Costs of Delays

The costs of an aircraft delay can be calculated by different methods (Cook, et al., 2004). Cook et al. (2004) provides a method for calculating delay costs and their impact. Interesting is especially the calculation of the costs for the “network reactionary delay” caused by a delay. The network effect is the effect of consequential delays caused either by the aircraft incurring the initial delay or by other aircrafts. These costs and effects can have a large influence on the overall number of delays (see Figure 3 – Reactionary delays). The specific cost elements for a delay are:

- Fuel burn costs plus commentary on airborne delay
- Maintenance costs
- Flight and cabin crew salaries and expenses
- Handling agent penalties
- Airport charges
- Costs of passenger delay to airlines

The average delay costs (without network effects) are about 47 US$/min. with network effects this value increases to 78 US$/min.
Cook and Tanner (2011) is an update of Cook et al. (2004) and divide the costs of a delay into strategic, tactical and reactionary costs. Strategical costs are accounted for in advance e.g. buffer, tactical costs are incurred on the day of operations and not accounted for in advance and reactionary costs are caused by network effects. In Europe for each minute of a primary delays another 0.8 minutes of reactionary delay were caused. These values can vary significantly from airline to airline. Ferguson et al. (2013) shows that the data and method from Cook et al. (2004) can also be applied to the US airline industry

Maintenance, Repair and Overhaul (MRO) companies want to reduce the costs in order to provide low cost maintenance services to airlines (Wagner & Fricke, 2006). For this they need to know how many unscheduled maintenance events can be expected and how many Man Hours (MH) they need to be able to handle. Wagner and Fricke (2006) present a method to estimate the number of needed MH to handle unscheduled maintenance for a given fleet.

4 UNSCHEDULED MAINTENANCE CAUSES

Unscheduled maintenance is caused by equipment that shows an unexpected fault during flight. This fault needs to be fixed before the next scheduled flight according to MEL. If it is not possible to fix the equipment during turn-around time (due to a long repair time, missing spare parts or difficult failure identification), the flight will be delayed until the fault is fixed. In extreme cases flights could get cancelled and passengers may have to be redirected or compensated. Figure 4 shows a typical sequence of events leading to unscheduled maintenance and delay (Sachon & Pate-Cornell, 2000).

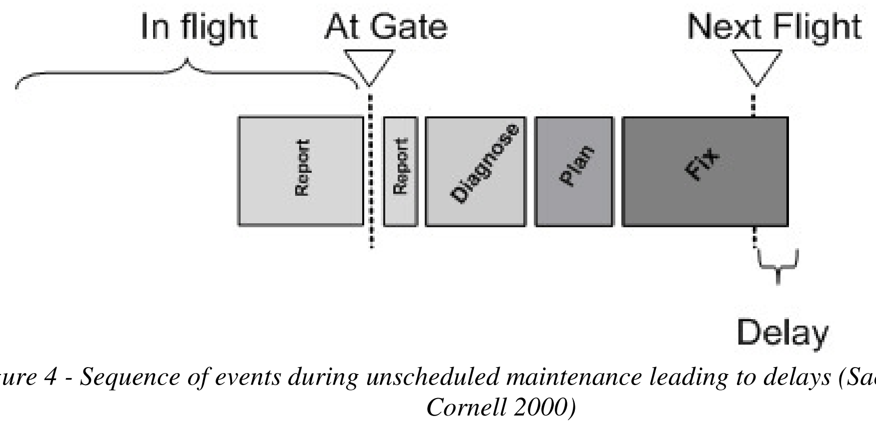

Figure 4 - Sequence of events during unscheduled maintenance leading to delays (Sachon and Patè-Cornell 2000)

Mechanical/technical reasons are not the only source for unscheduled maintenance. Humans are also an error source. Failure symptoms are misinterpreted or not noticed or new failures are introduced during scheduled maintenance (Civil Aviation Authority, 2009). This can have effects on the safety of the aircraft (Sachon & Pate-Cornell, 2000) or can lead to an increased number of NFF (International Air Transport Association, 2015). Incorrect or incomplete maintenance makes up to 61 % of all maintenance actions. Most cases of incorrect or incomplete maintenance are because parts are not correctly fitted or not set correctly (Civil Aviation Authority, 2009).

4.1 Aircraft, System and Database

The Airbus A340-600 was selected for this study, because it is quite new (entry into service in 2002) and but already enough experience and data is present. By November 2008, 84 aircrafts of the Airbus A340-600 were in service (Airbus SAS, 2008). Focus of the paper is on the air conditioning system (ATA (Air Transport Association) Chapter 21). The air conditioning system was chosen, because it is flight critical, monitored (auxiliary power unit (APU), fans …) and consists of a combination of mechanical and electrical. A lot of reliable information is available in the database of the Airbus In-Service Report (ISR) (Airbus SAS, 2008).

5 EMPIRICAL STUDY: AC SYSTEM OF A340

5.1 Delay Analysis

The delay analysis is done based on in-service data from Airbus (2008). The delays are evaluated for the air conditioning system of an A340-600 aircraft. This limitation is done to reduce the number of entries to check and to focus on the effects of one system. Also flight cancellations due to a fault were not taken into account. The delays caused by faults of the air conditioning are about 6 % (Airbus SAS, 2008) of the total number of delays caused by unscheduled maintenance. Figure 5 shows how the delay lengths of delays caused by the air conditioning of an A340-600 are distributed.

The magnitude of the delay costs caused by the air conditioning system is calculated, in order to show how important it is to reduce delays. Delay costs caused by the air conditioning system are calculated based on Cook et al. (2004) with updated economic data from Eurocontrol (2006). According to these sources, costs of a delay are assumed to be a linear function of delay time. The base value for delay costs is given in US$/min. The average delay costs (without network effects) are about 47 US$/min. With network effects this value increases to 78 US$/min. Based on Airbus SAS (2008), it is possible to calculate an average delay time caused by the air conditioning system of 90 minutes. Multiplying this value with the average delay costs (47 US$/min) yields delay costs of 4230 US$ for a 90-minute delay. In 50 % of the studied cases however, the delay is less than 50 min (see Figure 6). In these cases, the average delay costs are below 2350 US$. The total cost for 100 delays is about 432,990 US$. These costs are quite substantial, so any efforts to reduce delays are highly welcome.

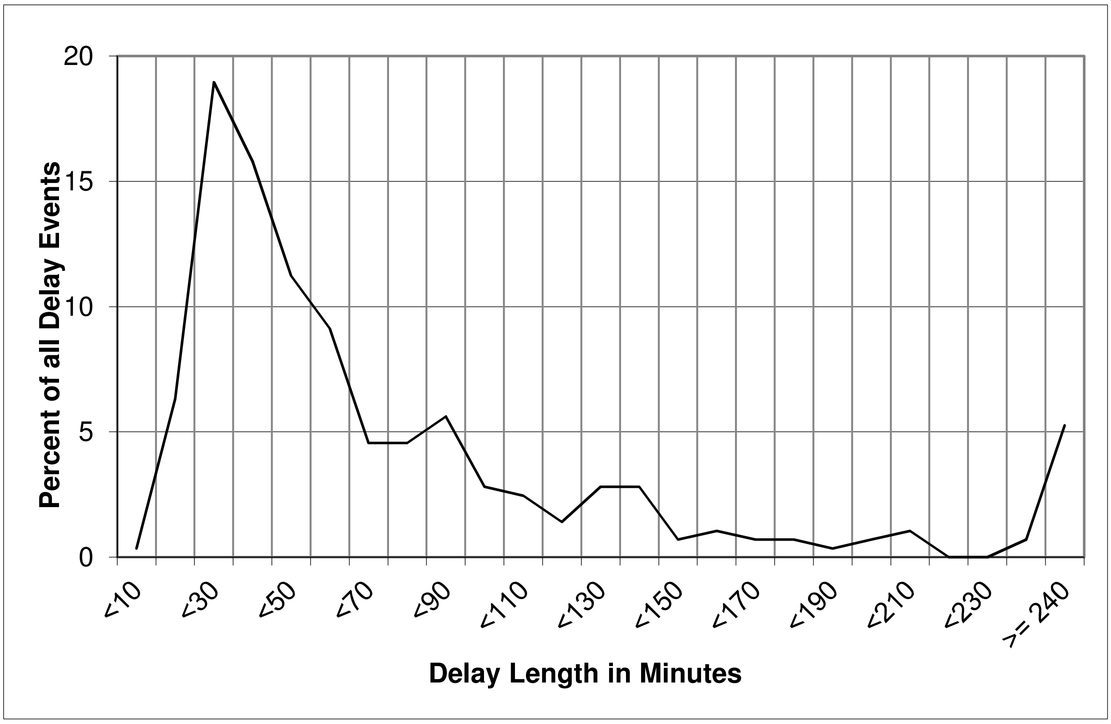

Figure 5 - Delay length distribution (Airbus SAS 2008a)

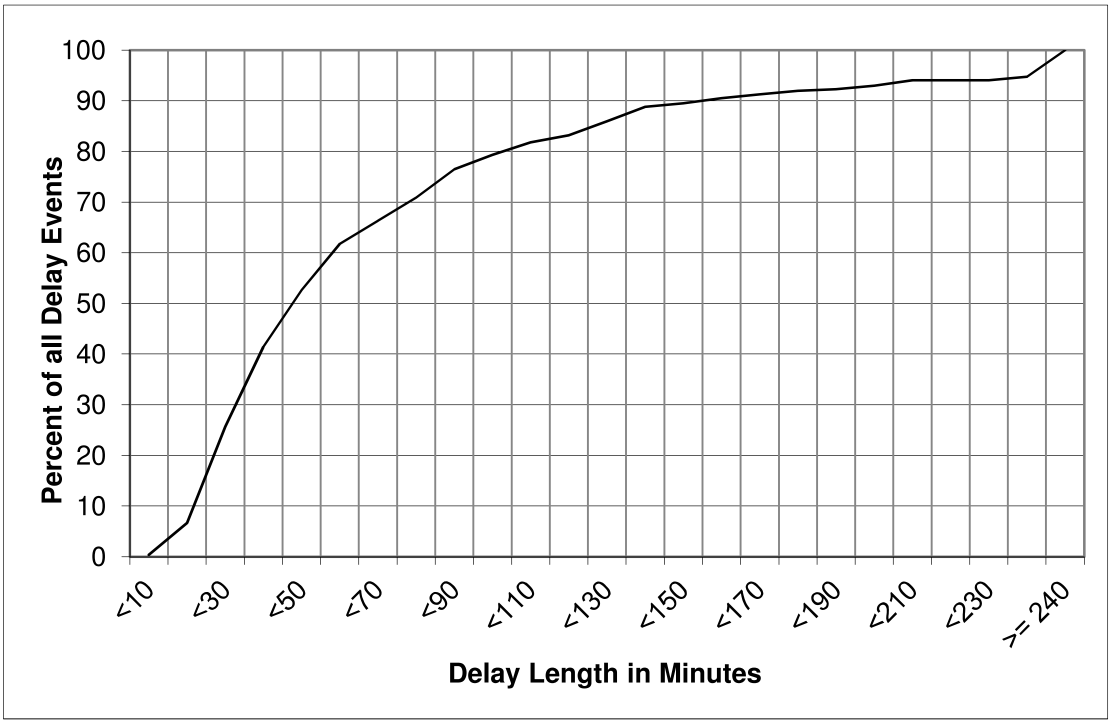

Figure 6 - Cumulative probability of delay (Airbus SAS 2008a)

5.2 Integrating Condition-Based Maintenance into Preventive Maintenance

To avoid unscheduled maintenance, different maintenance concepts have been developed. In preventive maintenance, components are replaced after a given period of time or in scheduled

intervals. In this way, maintenance is scheduled hopefully before the component shows a fault. In condition monitoring and trend analysis dynamic intervals are used.
The default aircraft maintenance strategy is preventive maintenance (Muchiri, 2012). Preventive maintenance is well established and understood in the aviation industry. The maintenance intervals for systems are constantly updated and optimized by in-service data (Ahmadi, et al., 2010).
Condition-based maintenance uses variable maintenance intervals for maintenance planning. These intervals are based on the system condition and the condition trend, if available. Condition-based maintenance is difficult to implement in the aviation industry because it can cause more maintenance actions if wrongly implemented (Shin & Jun, 2015) (Sondalini, 2015) and thus cause more delays. The goal should be not to increase the number of maintenance actions and ideally to reduce them. The following example shows this goal:

"For example, stadium lights burn out within a narrow period. If 10 percent of the lights have burned out, it may be accurately assumed that the rest will fail soon and should, most effectively, be replaced as a group rather than individually." (Mobley, 2002)

However it is possible to use condition-based maintenance to complement preventive maintenance. Preventive maintenance would still be the major maintenance strategy. Condition-based maintenance will be used to plan maintenance actions that are required outside of the maintenance intervals of preventive maintenance. This is the case if a system is stronger stress than planned. Reasons for this unplanned stress can be that the aircraft is mainly used in difficult environments or to other natural effects like heavy weather. Condition based maintenance can also help to detect incorrect or incomplete scheduled maintenance. Muchiri (2012) analysis the two different strategies and the gets the results that the difference between PM and CBM gets smaller for older aircraft because PM for older aircraft uses CBM principles.
Condition-based maintenance actions that are performed to prevent a failure before it occurs. This allows the aircraft operator to place the maintenance action outside of the regular flight traffic and thus to avoid unscheduled maintenance.

Regular maintenance intervals are unchanged to ensure airworthiness and to perform preventive maintenance actions.
Hölzel et al. (2014) showed a method how CBM can be used to optimize scheduled maintenance planning and what the benefits are.

5.3 New maintenance technologies as overinvestment in cost model

When designing a product, it is wise to make select production equipment that minimizes the global cost of maintenance during its service life. This equipment will require a higher initial investment to fulfill the same productivity requirements as cheaper equipment, but the costs of maintenance intervention and spare parts storage will be lower.

$$C_g = C_i + C_f + C_s + C_{oi}$$

To include over-investment in a global cost analysis, the initial price difference is amortized during the life of the equipment, making it possible to determine the extra investments required to minimize the other components of the cost.
The impact of overinvestments as avoided downtime cost

One of the most frequent problems when modeling financially maintenance systems is that the original costs have been modified several times in successive applications of methodologies or technologies that looked for the reduction of the global cost on the basis of costs what is called avoided.

In the indiscriminate implantation of policies of reduction of costs, three of the four parameters that constitute the global cost are affected

- Costs of interventions (Ci): Normally these are reduced in frequency and in volume then most of the predictive technologies secure a smaller aggressiveness in the failures with a reduction of corrective and an increase of the preventive ones.
- Costs of failures (Cf); Reduced in determined predictive policies where complete overhaul are replaced by small inspection which usually are performed without shut downing the process.
- Cost of over-sized investments (Csi): Perhaps, useless expensive equipment and plans of inspection are the most noticeably item in this cost because budget is increased but rarely are used and in consequence no added value to the process itself

In the following equation one can see the impact of the costs avoided with their double dimension, i.e. when a technology or concrete methodology implies an investment. That is to say, the cost of intervention and failure will be reduced with the application of the chosen technique intervention in a percentage, however, in the same way, the cost of overinvestment will increase if implanted technique is not interesting for the company and therefore it does not result in a return of investment.

$$C_g = C_i + C_f + C_a + C_{si} - C_{av}$$

$$C_g = (C_i - C_{av\_i}) + (C_f - C_{av\_f}) + C_a + (C_{si} + C_{av\_si})$$

5.4 Reduction of Delays and Costs by the means of CBM

It is assumed in this study that all delays that are not caused by the air conditioning system (e.g. oil smell which originates from the engines), that can be fixed by a reset action or that the maintenance crew was not able to find are not preventable. All other failures are preventable in theory (e.g. valve failures, leakages, fan faults, regulation faults …), by using condition monitoring and additional sensors (e.g. vibration monitoring …). Applying this assumption to the ISR database (Airbus SAS, 2008) shows that about 80 % of all failures are preventable (see Figure 8).

Counting their delay time with 0 minutes gives a new average delay of 40 minutes, which is a time reduction of 50 minutes or 56 % compared to the original A340-600 value of 90 minutes (see Figure 7). This also means a reduction of the average costs of delays caused by the air conditioning system by 2350 US$ or 56 %. The total costs for 100 delays is reduced by 382,250 US$ to 41,740 US$ or by 90 %. Figure 9 and Figure 10 show the distribution and probability of the preventable delays.

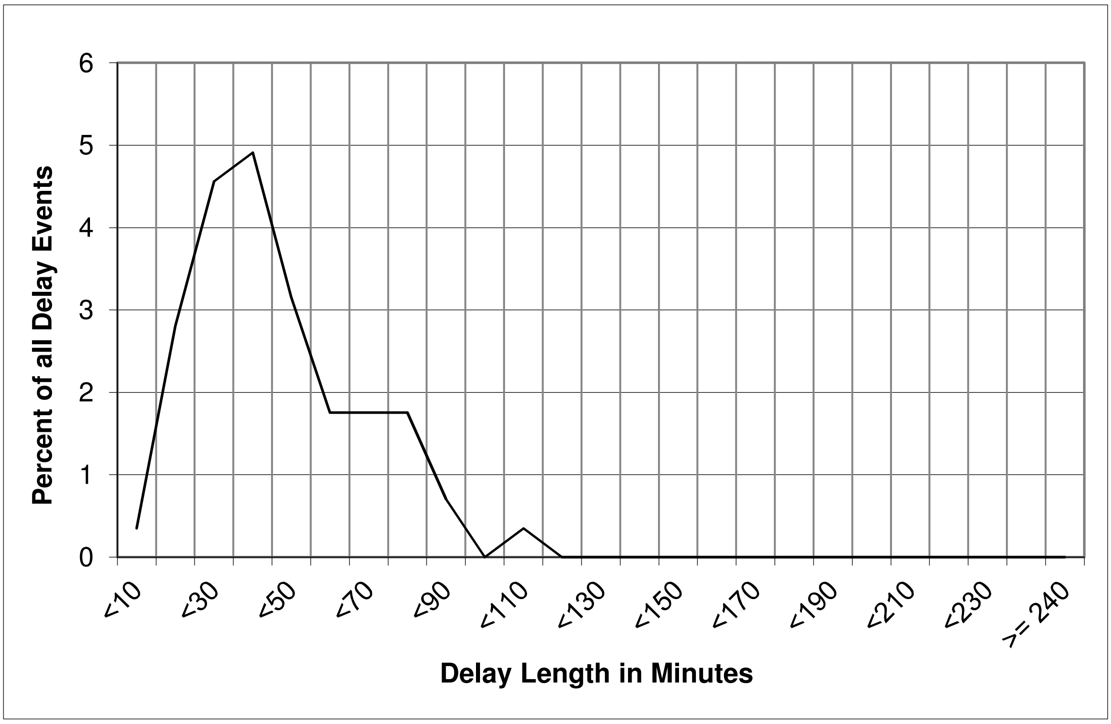

Figure 7- Delay length distribution of non-preventable faults

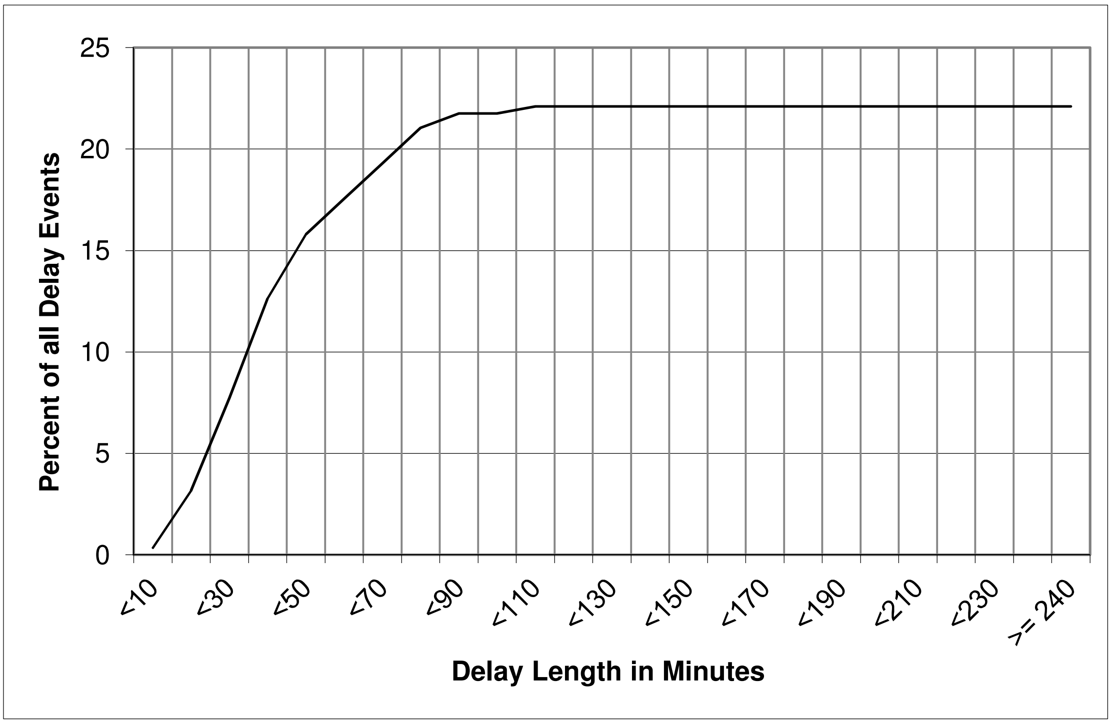

Figure 8 - Cumulative delay probability of non-preventable faults

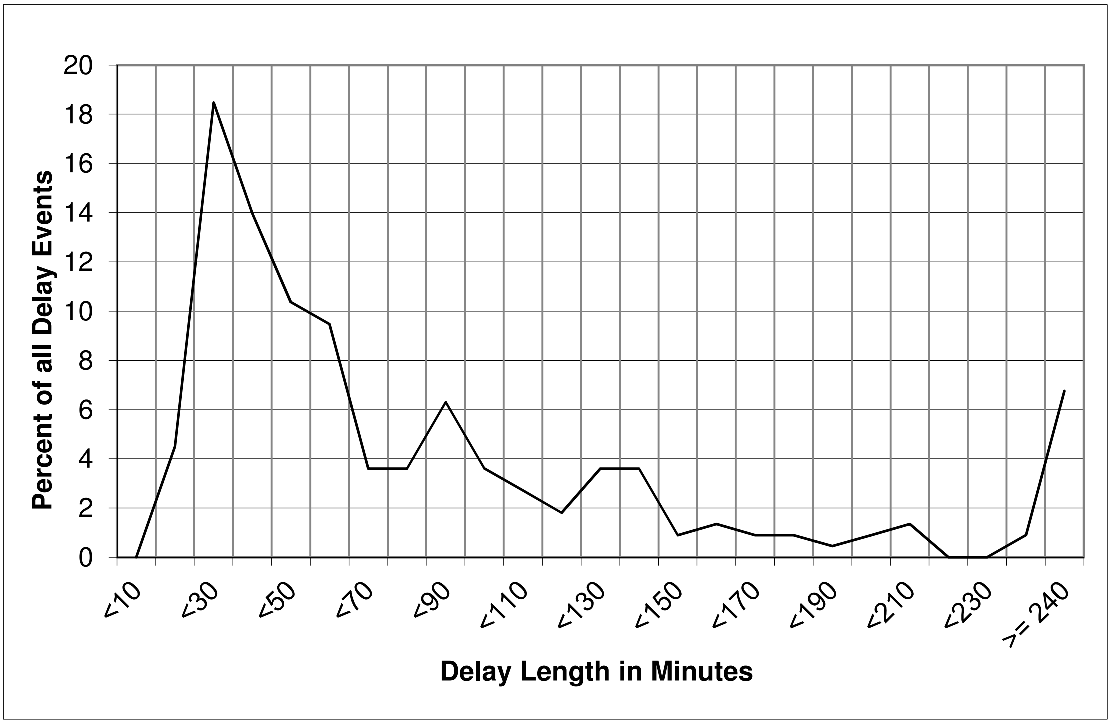

Figure 9 - Delay length distribution of preventable faults

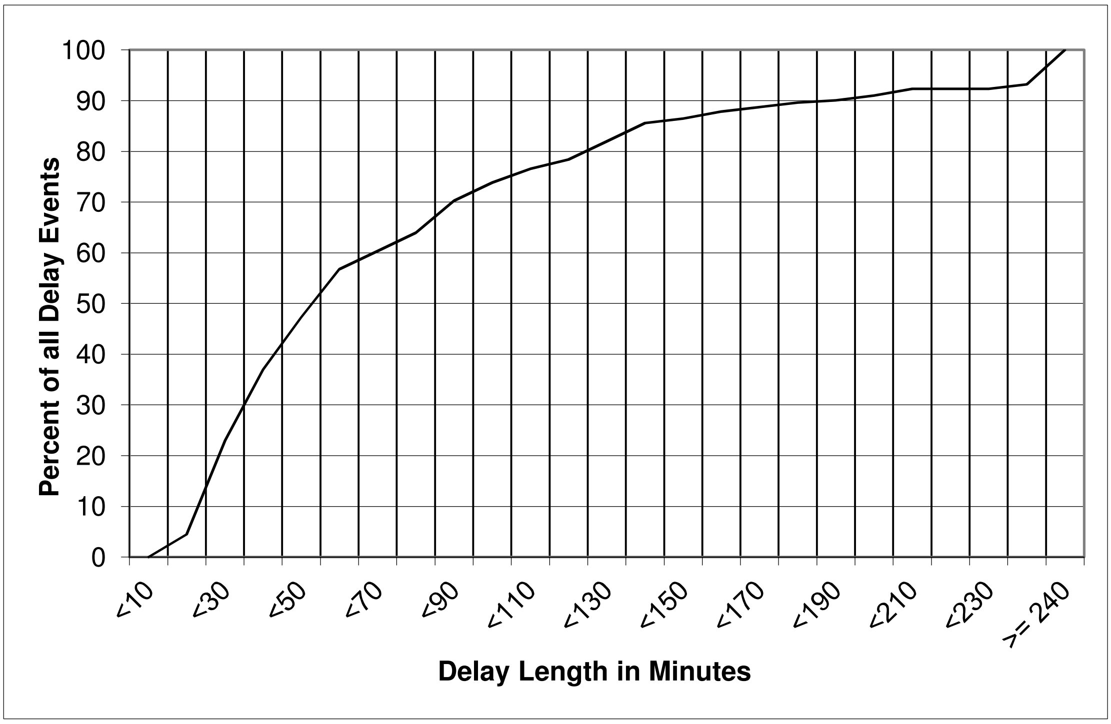

Figure 10 - Cumulative delay probability of preventable faults

The previous results assume that a good and reliable condition monitoring is available in all fault causing systems. However that is a very optimistic assumption that is not likely to be a realistic one in the near future. The following figures show how the results differ when it is assumed that only faults that occur in active system components that have already integrated sensors (fan faults, pack faults …) can be prevented and that other faults of other components (latches, connections, valves, sensors, leaks …) cannot be prevented.

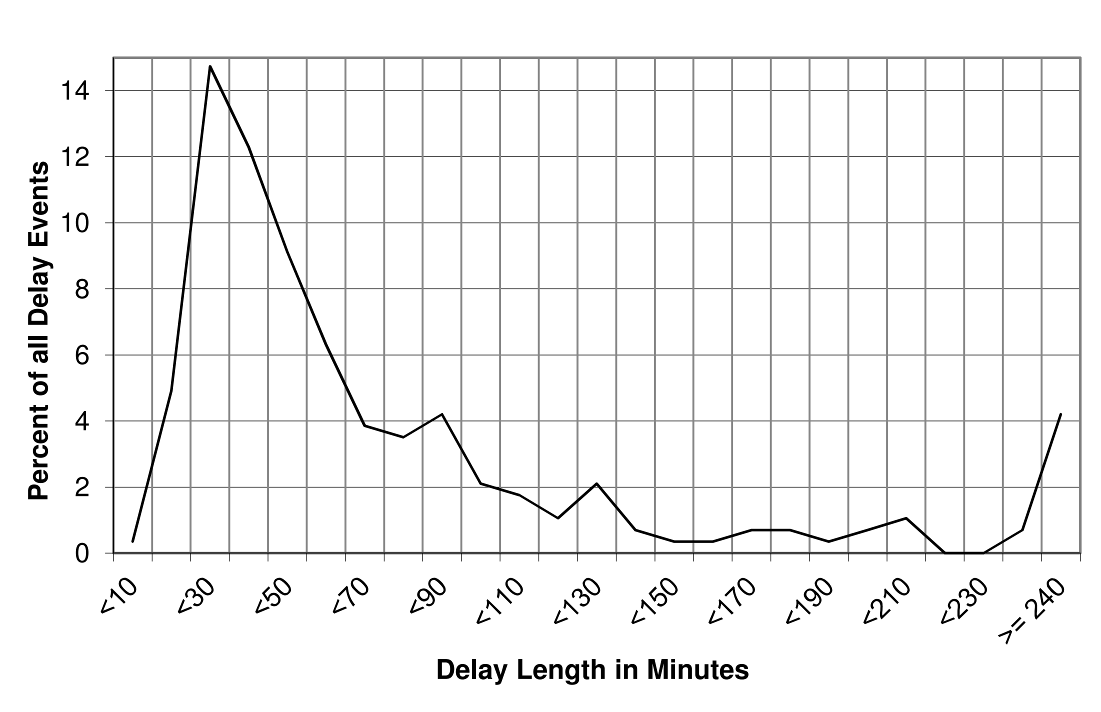

Figure 11 - Delay length distribution of realistically non-preventable faults

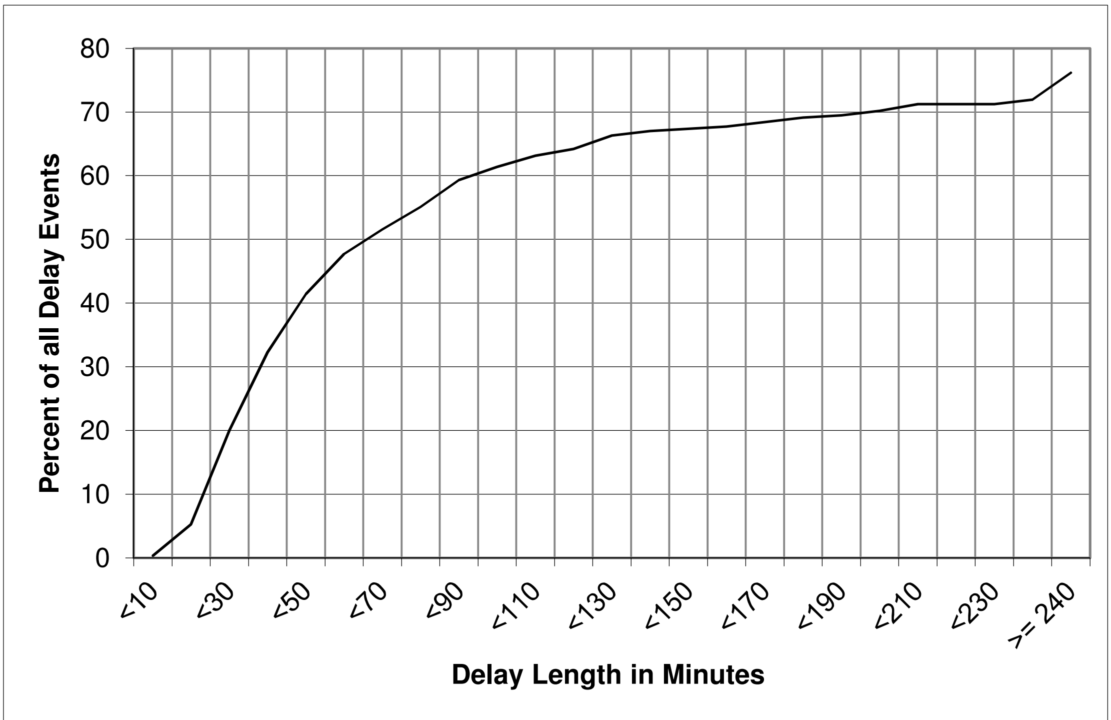

Figure 12 - Cumulative delay probability of realistically non-preventable faults

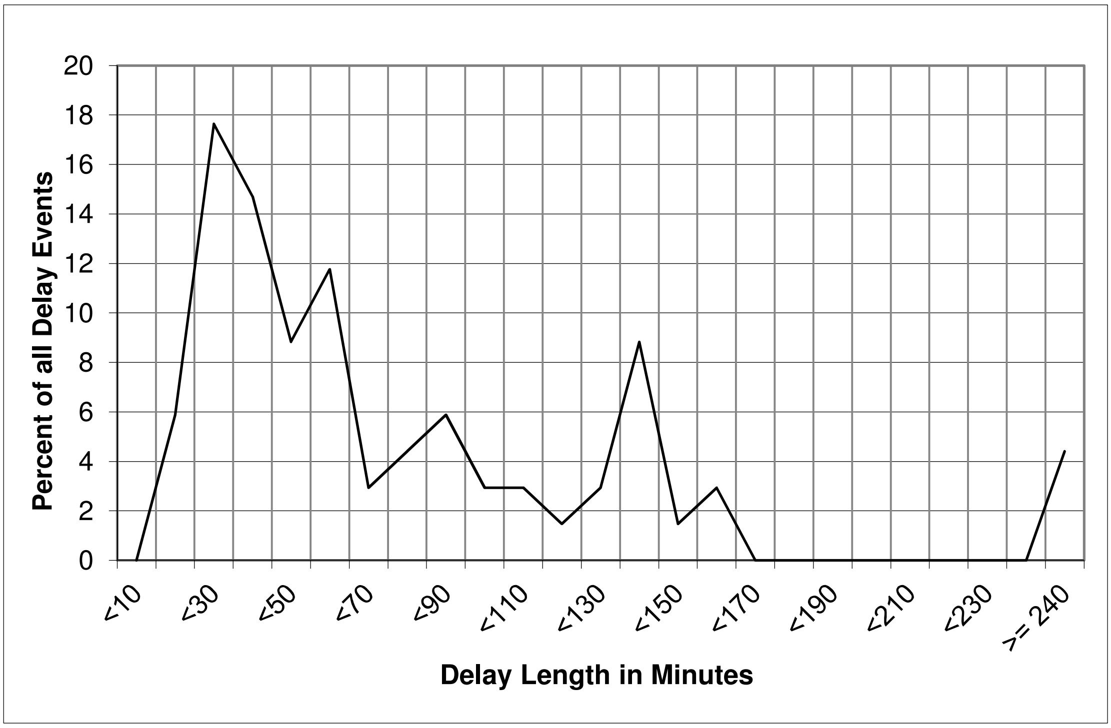

Figure 13 - Delay length distribution of realistically preventable faults

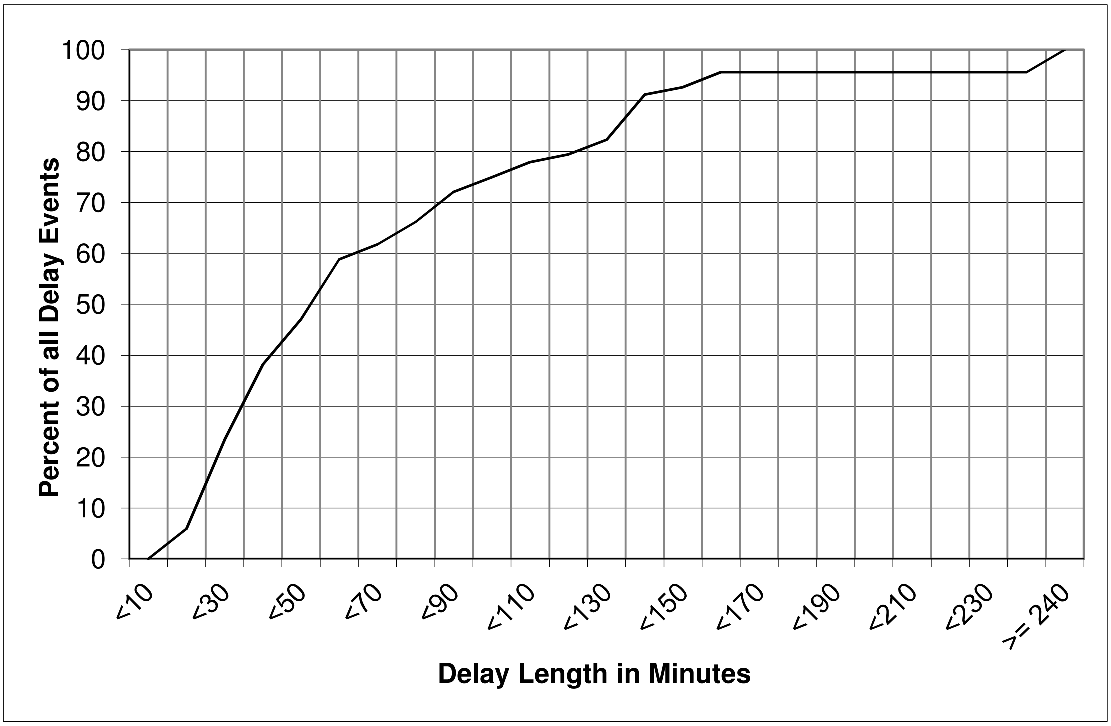

Figure 14 - Cumulative delay probability of realistically preventable faults

Figure 11 shows that most preventable delays are shorter delays and that only a few longer delays can be prevented. However some really significant delays that are longer than 170 minutes can be prevented Figure 12 shows that it is possible with a realistic assumption to prevent about 35 % of the delays, which is certainly a good goal to aim for. Figure 13 and Figure 14 show the distribution of the remaining delays. The average delay of the remaining delays is about 88 minutes and the average delay of the prevented delays is about 97 minutes. The total costs for 100 delays is reduced by 108,891 US$ to 315,097 US$ or by 25 %. Taking into account that only 6 % of unscheduled maintenance delays are caused by the air conditioning system means that the total delays costs are reduced by 1.5 %.

The cost saving calculations are done by using the 47 US$ per minute costs. All US$ values increase by 66 %.

5.5 Influence of CBM on Aircraft Costs

It is difficult to calculate the effect of CBM per flight hour, because only delays are analysed and delays occur on “per flight” base. The influence is stronger or weaker depending on the usage of the aircraft. So the delay costs cannot be mapped to the direct operating or direct maintenance costs. Instead the effect is analysed on a “per flight” basis. Thus the effects of CBM are based on the mission of the aircraft, when delays are considered.

CODA data for 2014 (Eurocontrol, 2015) shows that the average delay per flight for all causes is 9.7 minutes. 20% or 1.94 minutes of these delays are caused by technical issues (Knotts, 1999). This means that the air conditioning causes 0.12 minutes of delay per flight taking into account that 6% of the technical caused delays are caused by the air conditioning system. In US$ this means that the air conditioning causes costs of 5.5 US$ (using the 47 US$) per flight.

CBM can save 1.1 US$ per flight (if the delays are reduced by 20%) for the air conditioning system based on the results of the analysis. This value seems to be low, but if it will be multiplied by the number of flight per year, then the effect can be seen. Eurocontrol (2014) forecasts that there will be about 9,852,000 flights in Europe in 2015. In addition this cost saving can be achieved with no additional hardware. Only new software needs to be installed, that evaluates existing sensor data.

6 DISCUSSION AND CONCLUSIONS

This study shows that condition-based maintenance and trend analysis applied to components of the air conditioning system can most probably reduce delays from unscheduled maintenance by about 80 %. However it is very unrealistic to assume that condition monitoring will be available for most aircraft parts. It is more realistic to assume that the existing sensor in aircraft system will be used and thus that unscheduled maintenance delays can only be reduced by about 20 %. In addition aircraft maintenance regulations are very conservative and restricted. It would require a lot testing and verification to implement CBM in an aircraft environment and replace preventive maintenance, especially for flight critical systems. Using CBM to complement PM and for gathering data so that the preventive maintenance intervals can be optimized is possible, as long as scheduled PM maintenance actions are performed as required.

The major aircraft manufacturers (Airbus and Boeing) as well as airlines show an interest in trend analysis to reduce maintenance and thus to save costs and gain a higher aircraft usage. However significant work is needed to implement a good condition monitoring that makes useful predictions and not causes unnecessary work load. It would be optimal if existing sensors in the aircraft can be used for the condition monitoring, this however would reduce the number of possible detectable failure. Still it could possible to prevent the longer delays of more than 30 minutes. Given the large number of delays due to factors that are controllable by the airline it is worth to put more research and engineering effort into the reducing unscheduled maintenance events

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