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REDUCING DELAYS CAUSED BY UNSCHEDULED MAINTENANCE AND CABIN RECONFIGURATION

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Abstract
With respect to future trends in cabin design, this paper takes a close look at two problem areas that produce delays and reduce the time an aircraft is in the air. The first is related to unscheduled maintenance and the second is related to necessary cabin reconfigurations. Each of the two problem areas are analysed for time consumption and costs. The research project PAHMIR (Preventive Aircraft Health Monitoring for Integrated Reconfiguration, a cooperation project between Airbus Germany and Hamburg University of Applied Sciences) ads “intelligence” to aircraft components and novel technologies to the aircraft system. These measures will be able to reduce time consumption and costs for unscheduled maintenance caused by the air conditioning system in the order of 8 %. These measures will be able to reduce time consumption for cabin reconfiguration by about 36 %. The upper price limit for economic intelligent quick fasteners seems to be around 500 US$.

1 INTRODUCTION

Unscheduled maintenance
Unscheduled maintenance is caused by equipment that shows an unexpected fault during flight. 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 turn around time, the flight will be delayed until the fault is eliminated. By definition, *delays* are incurred when an aircraft is prevented from off-block to its destination for an interval of 15 min or more. To avoid unscheduled maintenance and possible delays, components are replaced after some time. In this way, maintenance is scheduled (hopefully) before the component shows a fault. In order not to waste life time of a component, a *trend analysis* of component parameters should help to predict the time of component failure and dynamically schedule a maintenance action shortly before the assumed failure is about to occur.

Reconfiguration
The task of an aircraft *cabin* is to transport the majority of the pay load of a passenger aircraft. The cabin accommodates the passengers in a safe and comfortable way together with their hand luggage. The baggage, on the other hand, is stored in the cargo compartment. In a cabin mainly *seats* and *monuments* cover the available cabin floor space. Monuments are cabin units like galleys and lavatories. Cabin *reconfiguration* means a change in the type or number of seats, monuments or other cabin components. Reconfiguration includes work tasks like removal, modification, installation and testing.

PAHMIR
The PAHMIR (Preventive Aircraft Health Monitoring for Integrated Reconfiguration) project investigates new technologies: a) for maintenance, based on trend analysis and b) for cabin components important for the reconfiguration process. By adding "intelligence" to components and novel technologies to the system, delays / time and costs can be saved.

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 [7].Focus in PAHMIR is on the air conditioning system (ATA[1] Chapter 21). The air conditioning system was chosen, because it is flight critical, monitored [3], consists of a combination of mechanical and electrical systems and is one of the cabin systems that cause most delays [1]. A lot of reliable information is available in the database of the Airbus In-Service Report (ISR) [4].

2 UNSCHEDULED MAINTENANCE

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 (Minimum Equipment List). If it is not possible to fix the equipment during turn around time, 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 1 shows a typical sequence of events leading to unscheduled maintenance and delay.

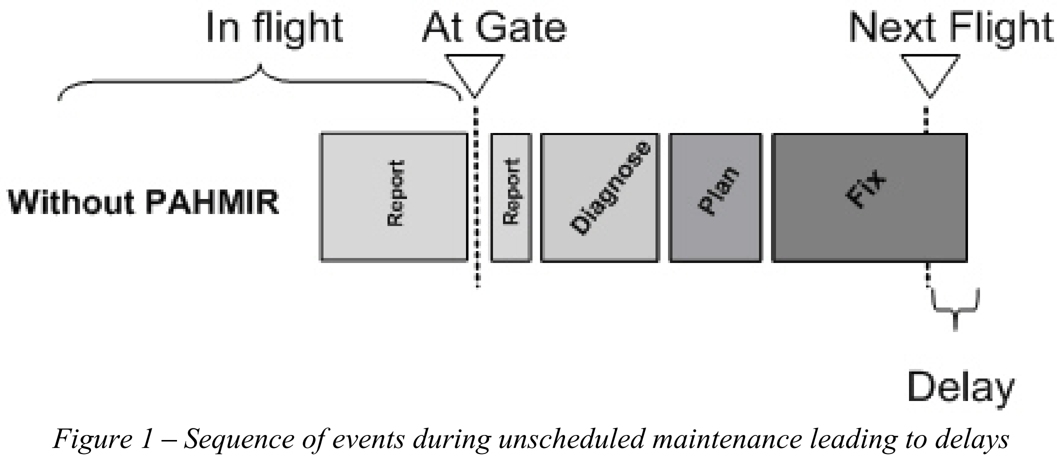

Figure 1 – Sequence of events during unscheduled maintenance leading to delays

[1] Air Transport Association of America

2.1 Delay Analysis

By definition, delays are incurred when an aircraft is prevented from off-block to its destination for an interval of 15 min or more [11]. Delays can originate from traffic, passengers, weather and the aircraft. A delay causes additional operating costs. Theses costs are crew-related, ramp-related, aircraft-related and passenger-related (hotel and meal, re-booking and re-routing, luggage complaints and revenue losses) [14]. Delay costs can be calculated from [10], [9] or [16].

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 base on [16] with updated economic data from [17]. 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$/min. The average delay costs (without network effects[2]) are about 47 US$/min. With network effects this value increases to 78 US$/min. Based on [4], it is possible to calculate an average delay time caused by the air conditioning system of 90 min. Multiplying this value with the average delay costs (47 US$/min) yields delay costs of 4230 US$ for a 90-minute delay. In 50 % of the studied cases however, the delay is less then 50 min (see Figure 2). In these cases, the average delay costs are below 2350 US$. These costs are quite substantial, so any efforts to reduce delays are highly welcome.

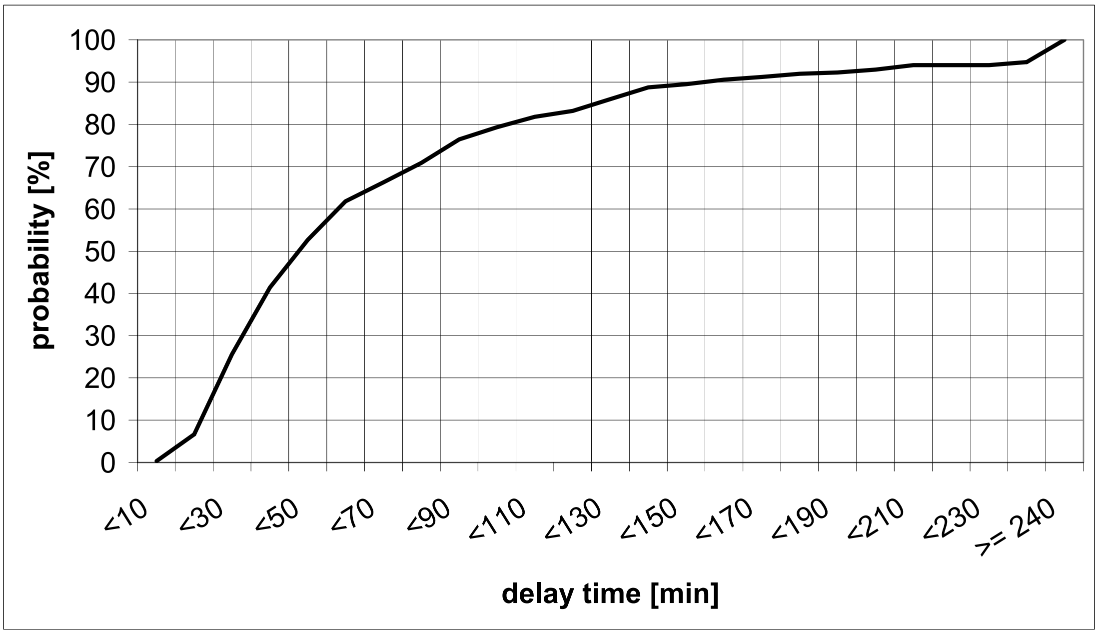

Figure 2 – Cumulative probability of delay time of the air conditioning system of the Airbus A340-600 based on data from [4]

2.2 Reduction of Delays and Costs

To avoid unscheduled maintenance, different maintenance concepts have been developed. In preventive maintenance, components are replaced after a given period of time. In this way, maintenance is scheduled hopefully before the component shows a fault. In condition monitoring and trend analysis dynamic intervals are used.

[2] The network effect is the effect of consequential delays caused either by the aircraft incurring the initial delay or by other aircrafts.

Preventive Maintenance
Preventive maintenance 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 [13]. Looking at preventive maintenance in more detail, three types can be identified [8]:

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.

Task Oriented Reliability-Centred Maintenance (RCM): 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.

Condition Monitoring
Condition monitoring constantly measures and analyses relevant mechanical and electrical component parameters during operation. Those parameters are selected for monitoring that allow 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 [13].

Trend Analysis
Trend analysis is an extension to condition monitoring. 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 [13].

Cost Reduction
Those mechanical faults of fans and valves were selected from the ISR database [4] that could have been prevented by using trend analysis based on vibration measurements. Analysis showed that 20 % of all faults in the air conditioning system could have been prevented. Counting their delay time with 0 min gives an average delay of 83 min, which is a time reduction of 7 min or 8 % compared to the original A340-600 value of 90 min. This also means a reduction of the average costs of delays caused by the air conditioning system by 329 US$ or 8 %. Calculating the average delay of the remaining incidents shows that the average delay increases to 102 min. This effect is caused by the fact that most faults that were potentially prevented caused delays less than 90 min. Figure 3 shows the cumulative probability with respect to delay time of the air conditioning system of the Airbus A340-600 assuming trend analysis has already been applied.

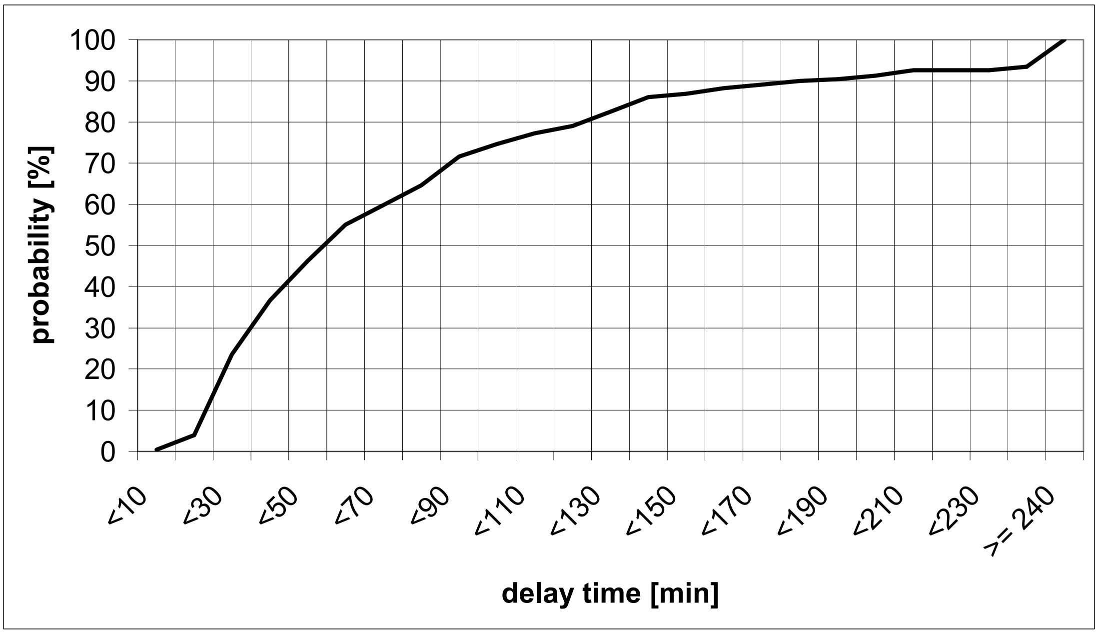

Figure 3 – Cumulative probability of delay time of the air conditioning system of the Airbus A340-600 assuming trend analysis would have been applied

3 CABIN RECONFIGURATION

Aircraft cabins have various *classes*. First class (F/C), business class (B/C) and Yankee class (Y/C) are the basic classes. The Yankee class is also called economy class. The classes can be differentiated by their level of comfort. Most important for the level of comfort is seating space. In a cabin mainly *seats* and *monuments* cover the available cabin floor space. Monuments are cabin units like galleys or lavatories.

Cabin reconfiguration means a change in the type or number of seats and monuments. Many other reconfiguration tasks are possible. Two forms of cabin reconfiguration can be differentiated: In *class resizing,* one cabin class is enlarged whereas another class is reduced in size. In *monument shifting*, monuments are assigned a different location in the cabin. The focus of this study is class resizing.

Cabin reconfiguration can be divided into five **subtasks** [2] are: *Removal*: Mechanically and electrically installed components are removed from the cabin. The number and type of components that need to be removed depend on the reconfiguration scenario. *Modification*: Modification includes all tasks that are needed to prepare the new installation area. This includes cleaning, change of wiring, oxygen and system routing. *Installation*: Installation includes all tasks that are needed for installation of the new cabin layout. During installation all mechanical and electrical components need to be installed and configured for the new cabin layout. *Testing*: Testing includes all procedures and tasks to ensure the new cabin layout is sound. The new layout has to be tested to confirm that all components are installed correctly and that the correct components are installed. Both software and hardware is tested during this step. Testing time does not depend on the number of installed components, because testing is done in parallel. Tests are done for the complete reconfigured cabin. *Troubleshooting*: Troubleshooting tasks need only to be performed, if tests showed a failure during testing. Removal and installation tasks can become part of troubleshooting.

Cabin components that are affected by reconfiguration include: seats, Passenger Service Units (PSU), stowage's, class dividers, carpets, lavatories, galleys and panels. This is not a complete list of all affected components and not all cabin components are affected by reconfiguration, e.g. if two rows of business class (B/C) seats shall be removed and three rows of Yankee class (Y/C) seats shall be installed, then only the affected seat rows, PSU, ceiling panels and class dividers need to be modified.

Quick cabin reconfiguration is demanded more and more by airlines to be able to adapt an aircraft to different flight routes. The goal is to be able to do class resizing during turn around and monument shifting during one night.

3.1 Process Time Analysis

Worked example: A very common task in reconfiguration is to remove Y/C seats and replace them with B/C seat or vice versa. For the analysis of the process, the **example reconfiguration scenario**, consisting of the removal of 12 B/C seats, replacement by 36 Y/C seats. The time is given as a percentage of the total reconfiguration process time. For the study, the time of individual reconfiguration subtasks in the class resizing process was analyzed. Improved hardware and software solutions for these subtasks help to reduce testing time.

More complex reconfigurations, like those involving lavatories and galleys, are presently done in a hangar. In the close future it will still be unlikely to see these big reconfigurations taking part during turn around on the apron.

Table 1 – Relative process time for the example reconfiguration scenario

Process	Workers	Time
Removal		**24.0 %**
Seat rail cover removal	3	1.5 %
B/C seat de-installation from seat rail	6	7.5 %
B/C seat de-installation	6	7.5 %
B/C seat removal	6	7.5 %
Modification		**12.4 %**
Cleaning of seat rails	6	3.7 %
Secondary structure	6	5.0 %
Oxygen	2	3.7 %
Installation		**34.0 %**
Y/C seat transportation into aircraft	8	4.5 %
Y/C seat positioning into seat rail	8	4.5 %
Y/C seat installation (mechanical)	8	4.5 %
Seat rail cover installation	6	1.0 %
IFE (In-Flight Entertainment) connection	1	7.5 %
PSU connection	3	11.0 %
Y/C seat installation (electrical)	3	1.0 %
Testing		**29.6 %**
Test of the passenger call system		3.0 %
Test of the Passenger Supply Channel (PSC)		7.5 %
Illumination test		5.6 %
In-seat power supply test		3.0 %
Test of the IFE seat component		3.0 %
Test of seats		7.5 %
Total		**100.0%**

The *relative process time* for the above specified example reconfiguration scenario is presented in Table 1. The process time was taken from [2] with selected measurement results explained in [5]. Table 1 shows that about 30 % of the reconfiguration time is taken up by testing. Also 4.5 % of the time is used to position the seat into the seat rail and about 13.5 % of the time is used for testing operation of the seat. It is also interesting to note that mechanical seat installation and removal takes up 12 % of the reconfiguration time. Hence 60 % of the time is taken up by tasks that can be facilitated by process improvements as proposed in the next section.

3.2 Reduction of Process Time and Costs

Component Abilities

The PAHMIR project wants to reduce the reconfiguration time by adding “intelligence” to components [15] and novel technologies to the system. The intelligence includes the following component abilities:

Component Self Identification allows a component to know what kind of component it is and how it can communicate with a configuration management in the aircraft cabin. By giving each component an identity, about 30 % of the software installation time can be saved. The software that was normally installed during the reconfiguration is now on-board the component and does not have to be installed on the aircraft.

Component Location Detection enables a component to know where it is installed in the cabin. A component can detect its location at any time, when the location detection system is turned on. With location detection it is possible to reduce the time needed for seat positioning into seat rail and later for troubleshooting. It also helps to reduce configuration time together with identification. First experience was gained with seat positioning by location detection and showed a process time reduction of 40 %.

Component Self Testing allows a component to use the installed testing equipment to start and run self tests as soon as it has power. Only Passenger Supply Channel (PSC) tests and seat tests are reduced by self testing during reconfiguration. The time saving is achieved by self testing in parallel and does not depend on a finished installation of the cabin. Measurements showed that the time needed to perform a single seat and PSC self test is only about 20 % of the complete testing time. A testing time reduction by 80 % means that the time to test a seat falls below the installation time of one seat ($0.2 \cdot 7.5\ \% < 4.5\ \%$). It follows that if a seat test is finished before another seat is installed and at the end of the seat installation only one seat is remaining to be tested.

With **Quick Fastening** it is possible to reduce the reconfiguration time significantly, because mechanical unlocking the locking mechanisms takes a significant amount of the time. Experiments showed that with a quick fastening technology, e.g. TZ Intevia fasteners [18], it is possible to reduce the time for fastening and loosening by 90 %.

Time Saving Potentials

Taking the above component abilities and apply them to the above **example reconfiguration scenario**, where 12 B/C seats were exchanged against 36 Y/C seats, results in considerable time savings.

Time Saving for Removal: For the removal process the following time saving is possible due to the recommended technologies. For removal it is possible to save 7,0 % of the total removal time and about 30 % of the removal time (Table 2).

Table 2 – Time saving for the removal in an example reconfiguration scenario

Process	Old Time	New Time	Saving
Removal	24.00 %	17.25%	6.75 %
Seat rail cover removal	1.50 %	1.50 %	0.00 %
B/C seat de-installation from seat rail	7.50 %	0.75 %	6.75 %
B/C seat de-installation	7.50 %	7.50 %	0.00 %
B/C seat removal	7.50 %	7.50 %	0.00 %

Time Saving for Modification: With intelligent and quick fastening it is possible to reduce the time for modification of the secondary structures. For modification it is possible to save 4,5 % of the total reconfiguration time and about 30 % of the modification time (Table 3).

Table 3: Time saving for the modification in an example reconfiguration scenario

Process	Old Time	New Time	Saving
Modification	12.40 %	7.90 %	4.50 %
Cleaning of seat rails	3.70 %	3.70 %	0.00 %
Secondary structure	5.00 %	0.50 %	4.50 %
Oxygen	3.70 %	3.70 %	0.00 %

Time Saving for Installation: For the installation process the following time saving is possible due to the recommended technologies. For installation it is possible to save 8 % of the total reconfiguration time and about 24 % of the installation time (Table 4).

Table 4 – Time saving for the installation in an example reconfiguration scenario

Process	Old Time	New Time	Saving
Installation	34.00 %	25.90 %	8.10 %
Y/C seat transportation into aircraft	4.50 %	4.50 %	0.00 %
Y/C seat positioning into seat rail	4.50 %	2.70 %	1.80 %
Y/C seat installation (mechanical)	4.50 %	0.45 %	4.05 %
Seat rail cover installation	1.00 %	1.00 %	0.00 %
IFE connection	7.50 %	5.25 %	2.25 %
PSU connection	11.00 %	11.00 %	0.00 %
Y/C seat installation (electrical)	1.00 %	1.00 %	0.00 %

Time Saving for Testing: Time saving for testing is mainly achieved through parallel self-testing. For the testing process the following time saving is possible mainly due to self-testing. For testing it is possible to save 17 % of the total reconfiguration time and about 56 % of the testing time (Table 5).

Table 5 – Time saving for the testing in an example reconfiguration scenario

Process	Old Time	New Time	Saving
Testing	29.60 %	12.80 %	16.80 %
Test of the passenger call system	3.00 %	3.00 %	0.00 %
Test of the PSC	7.50 %	1.50 %	6.00 %
Illumination test	5.60 %	5.60 %	0.00 %
In-seat power supply test	3.00 %	0.60 %	2.40 %
Test of the IFE seat component	3.00 %	0.60 %	2.40 %
Test of seats	7.50 %	1.50 %	6.00 %

Total Time Saving: Combining the tables of the above example give the total time saving of the *example reconfiguration scenario*. Table 6 shows the results. Reconfiguration time can be reduced by 36 % in this example. The reduction can vary depending on the reconfiguration scenario (different duration, complexity and processes), but in this common scenario a significant process improvement was shown.

Table 6 – Total time saving in an example reconfiguration scenario

Process	Old Time	New Time	Saving
Total	100.00 %	63.85 %	36.15%
Removal	24.00 %	17.25 %	6.75 %
Modification	12.40 %	7.90 %	4.50 %
Installation	34.00 %	25.90 %	8.10 %
Testing	29.60 %	12.80 %	16.80 %

Time Saving for Troubleshooting: To show the possibility of time saving for troubleshooting, another example is selected. It is assumed that a seat with a defect IFE unit was installed. Two workers are involved in this troubleshooting task. Table 7 shows the tasks that need to be done and the possible time savings that amount in total to 20 %.

Table 7 – Time saving for the troubleshooting of a seat related IFE fault

Process	Old Time	New Time	Saving
Troubleshooting	**100.00 %**	**80.50 %**	**19.50 %**
Fault analysis	7.50 %	7.50 %	0.00 %
Removal	26.00 %	19.25 %	6.75 %
Seat rail cover removal	3.50 %	3.50 %	0.00 %
Y/C seat de-installation from seat rail	7.50 %	0.75 %	6.75 %
Y/C seat de-installation	7.50 %	7.50 %	0.00 %
Y/C seat removal	7.50 %	7.50 %	0.00 %
Installation	66.50 %	53.75 %	12.75 %
Y/C seat transportation into aircraft	7.50 %	7.50 %	0.00 %
Y/C seat positioning into seat rail	7.50 %	4.50 %	3.00 %
Y/C seat installation (mechanical)	7.50 %	0.75 %	6.75 %
Seat rail cover installation	2.50 %	2.50 %	0.00 %
IFE connection	9.00 %	6.00 %	3.00 %
PSU connection	30.00 %	30.00 %	0.00 %
Y/C seat installation (electrical)	2.50 %	2.50 %	0.00 %

Cost Saving Potentials

The cost savings for the given *example reconfiguration scenario*, where 12 B/C seats were exchanged against 36 Y/C seats, are calculated in this subsection. First the budget, which the airline will save by the reduced reconfiguration time, is calculated. Then the maximum price of the new component that enables to save time and money is calculated. For this study it is assumed that the costs of ownership (COO) for the aircraft are 10 US$/min as calculated by [16] and [17] and maintenance related burdened labor costs are 10 US$/min [12]. So the total costs for the reconfiguration example are 20 US$/min. The reconfiguration time for the given example is assumed to be eight hours (480 min) with current (2008) technologies and enough trained personal on the job [6]. For the new process, a time consumption of 306.5 min (480 min · 0.635 = 306.5 min) is calculated. Taking the assumed costs and applying them to the current reconfiguration (480 min · 20 US$/min = 9600 US$) and the modified reconfiguration process (306.5 min · 20 US$/min = 6130 US$) gives the resulting savings as shown in *Table 8*.

Table 8 – Reconfiguration costs

	Old Process	New Process	Saving
Costs	9600 US$	6130 US$	3470 US$

Upper Price Limit for Intelligent Quick Fasteners

Within the PAHMIR project it is planned to develop intelligent quick fasteners, which include nearly all of the technologies that are needed to achieve the proposed cost saving. These fasteners are more expensive then currently used fasteners and thus their costs have to be compared against the cost saving for reconfiguration. According to [6] a typical reconfiguration frequency is twice a year. Applying this frequency to the total life of an aircraft (30 years) gives 60 reconfigurations during the aircraft lifetime. This means at least 60 reconfigurations are needed to reach the breakeven point. In Table 8 savings of 3470 US$ are shown. The basis for the calculation is the two-class cabin layout of the A340-600 (36 B/C seats at 40 inch pitch and 383 Y/C seats at 32 inch pitch). Every seat row (consisting of two seats) needs to be fixed with two intelligent quick fasteners. This means 419 fasteners have to be installed. Based on the above assumption, the following breakeven point is calculated:

$$0 = 3470 \text{ US\$} \cdot 60 - 419 \cdot x \Rightarrow x = 497 \text{ US\$} \tag{1}$$

Equation (1) shows that the breakeven point is reached within 60 reconfigurations, if the upper price limit for one fastener is below 497 US$.

The example cabin reconfiguration is a simple reconfiguration scenario and much more complex reconfigurations (e.g. including monument reconfiguration) are planned by airlines. In these scenarios the absolute cost saving is much higher.

4 SUMMARY

This study shows that trend analysis applied to components of the air conditioning system can most probably reduce delays from unscheduled maintenance by about 8 %. An example calculation shows that time consumption can be reduced due to improved reconfiguration concepts by about 36 %. The upper price limit for economic intelligent quick fasteners seems to be around 500 US$. The PAHMIR project tries to integrate technologies, which are necessary to gain these advantages, into a single component. This will be reached by combining trend analysis with location detection, component self testing, component identification and quick fastening technologies. The major aircraft manufacturers (Airbus and Boeing) as well as airlines show an interest in quick cabin reconfiguration and trend analysis to reduce maintenance and reconfiguration times and thus to save costs and gain a higher aircraft usage.

5 ACKNOLEDGEMENT

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