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DIGITAL TRANSFORMATION IN MAINTENANCE ON THE EXAMPLE OF A TIRE PRESSURE INDICATING SYSTEM

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Abstract

The digital transformation is getting increasingly important in the aviation industry to gain competitive advantages. Thus, digital services, like Aviatar (Lufthansa Technik) and Skywise (Airbus), have been introduced recently and are receiving much focus in the industry and research. Research in identifying profitable systems for an automated condition monitoring and the evaluation of their respective operational and economic impact is still at an early stage in the aviation industry. In this paper, we provide a methodology for the identification of digitalization potentials. By combining the approach of the Open System Architecture – Condition Based Maintenance (OSA-CBM) model with a process oriented model, both, specific measures for the improvement of a system's maintenance as well as suitable systems for the implementation of digitalization technologies, can be derived. With the developed method, the potential layout of an Automated Condition Monitoring System (ACMS) is shown on the example of a Tire Pressure Indicating System (TPIS). To quantify the benefit of such a system, a parametric study for the simulated tire pressure loss is conducted using a Monte Carlo simulation. The obtained results allow an estimation of the operational impact by an improved maintenance schedule as well as the determination of the total cost reduction by using such a condition monitoring system.

1 INTRODUCTION

To gain and keep competitive advantages, the implementation of digital technologies throughout the whole aviation industry is getting increasingly important. As a promise to expand into new markets and allow insights in the utilization as well as degradation of aircraft, digital services, like Aviatar from Lufthansa Technik and Skywise from Airbus, have been introduced recently. These platforms receive much focus from industry and research.

Research in identifying profitable systems for a continuous condition monitoring and the evaluation of their operational and economic impact is still at an early stage in the aviation industry. Therefore, the full possibility of continuously monitored systems has not been exploited, yet. In this paper, we provide a methodology for the identification and calculation of digitalization potentials for the Airbus A320 and validate the approach with the concept of an ACMS.

By combining the approach of the Open System Architecture – Condition Based Maintenance (OSA-CBM) model by MIMOSA [1] with a process-oriented model, both, specific measures for the improvement of a system's maintenance as well as suitable systems for the implementation of digitalization technologies, can be derived. We chose the TPIS for the implementation of an automated maintenance system, as it already has sensors equipped to allow operators to monitor the tire pressure. Therefore, it is in one of the more advanced stages of the OSA-CBM model.

To quantify the benefit from such a system in maintenance, a parametric study for the simulated tire pressure loss is conducted using a Monte Carlo simulation. The daily pressure loss is simulated with random, normally distributed pressure drops each day. The obtained results allow an estimation of the operational impact by an improved maintenance schedule as well as the determination of the maintenance cost reduction by using such an ACMS for tires.

Based on the information given in the Maintenance Planning Document (MPD) [2], 12.17 man-hours (MH) can be saved per A320 aircraft and year by replacing regular, manual pressure reading tasks with an automated monitoring system. For a large hub-and-spoke airline with approximately 130 narrow-body aircraft [3] of this or similar types, the saving amounts to 1,582 MH per year. For all 2,137 in-service-aircraft of the A320 [4] series within Europe, the total time saving potential equals 26,000 MH per year.

2 STATE OF THE ART

The regular activities to maintain an aircraft are described by the aircraft manufacturer in the MPD. The tasks within the MPD are necessary for systems, components, and the structure for the aircraft to remain in a safe and airworthy condition. In addition to the description of the maintenance activity, the MPD includes the time interval between repetitive executions and the man hours needed to perform the activity. In Table 1, the tire pressure reading task for an A320 is shown.

Table 1: A320 MPD Tire Pressure Check [2]

Description	100% Interval	Men	Task MH	Applicability
Wheels – Functional Check of Tire Pressures	3 DY	1	0.10	All

As it can be seen, the MPD defines three days as the interval for the pressure check of all tires of the A320 aircraft and estimates 0.1 MH for the execution. For aircraft without a TPIS, the pressure check is performed manually using a Tire Pressure Gauge (TPG). If a TPIS is installed, the pressures are checked with the help of the wheel page in the Electronic Centralized Aircraft Monitoring system (ECAM). Especially for large aircraft with numerous tires, this could reduce the maintenance task duration.

Modern TPIS also provide alerts for low tire pressure or high differential pressures on one axis. In the current system, the tire pressure information is just displayed and neither stored nor transmitted to a ground station. [5] Additionally, as the maintenance task defines a waiting time after the last flight [6], we assume that no temperature compensation is done by the system itself.

Besides the aircraft manufacturer, tire manufacturers provide recommendations for the maintenance of the tires themselves. These instructions may differ from the ones of the aircraft manufacturer. In contrast to the MPD, Goodyear, as a tire manufacturer for A320s, recommends a daily pressure check. Goodyear also defines a tolerance of overinflation up to 5% of the specified tire pressure as an acceptable range for normal tire operation. Furthermore, a pressure drop of up to 5% within 24 hours is tolerated without the tire being declared defective. Manufacturer tests have shown that an underinflation of 5% results in a reduction of a tire's life by 50%. An underinflation of 10% reduces the expected life time to 25% of the normal life time [6].

Once a pressure loss beyond a specified threshold is detected, the tire has to be refilled. For this purpose, Nitrogen is used as it can contribute to fire protection. If there is a temperature difference of more than 27°C between the airport of departure and destination, the pressure should be adjusted accordingly to account for pressure variations as a result of temperature differences. This will help to avoid impermissible underinflations in excess of 10% to preserve the tire's life time. This fact should also be considered if tire pressure has been checked in a heated hangar, but the aircraft is used at much lower outside temperatures. [6]

3 DIGITAL TRANSFORMATION APPROACH

The digital transformation of the previously presented tire maintenance process is driven by the objective of an Automated Condition Monitoring System for the tire pressure inspection. The implementation of an ACMS enables the optimization of the tire maintenance process by reducing the execution of avoidable service and repair tasks. In particular we investigate which digital technologies need to be implemented in order to transform the state of the art system into a new ACMS. The architecture of this new system follows a combination of the OSA-CBM framework (Figure 1) and the digitalization approach by SCHUH [7] (Figure 2).

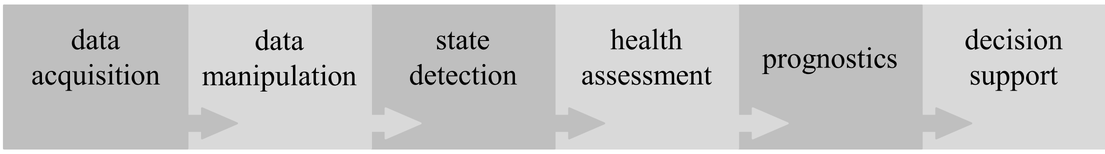

Figure 1: The OSA-CBM Framework [1]

Within the OSA-CBM framework, raw sensor data is acquired, manipulated, and transformed into useful information to detect a certain state of a technical system. Subsequently, the detected state is used to assess the health of the system by putting the information into a physical background. From that, the Remaining Useful Life (RUL) of the system can be derived. Based on the RUL, a future condition of the system can be predicted. It follows that the information about current and future conditions of the technical system can be used to decide about enhanced operation and maintenance of the system. [8] To create an efficient condition monitoring system for the tire pressure inspection, a reliable decision support for the execution of service and repair tasks has to be developed.

For the automation of the condition monitoring system, digitalization is an essential key element. The stated digitalization approach shows how to increase the benefit of a system by increasing the digitalization level step by step. In this approach, digitalization starts with the computerization of a system's subsystems and the generation of digital data. Subsequently, the data from the subsystems is connected to create visibility of all relevant parameters and conditions of the overall system. As a next step, system data is combined with physical knowledge to obtain information. At this point, it is possible to understand the system's be-

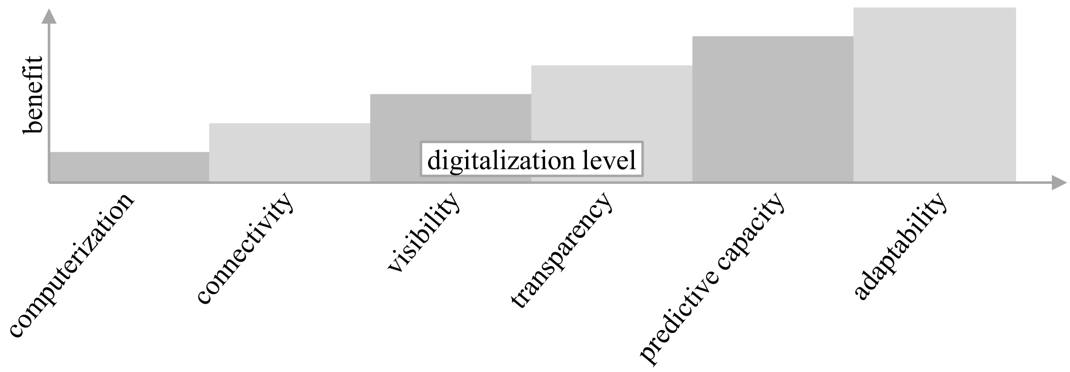

Figure 2: Digitalization Approach [7]

havior by observing measurement data and, therefore, to achieve transparency of the system. By projecting the information about the current state into the future, predictive capacities are available. A prediction system allows users to prevent errors before they occur with the help of simulations. Adaptability is the highest digitalization level of this approach, incorporating autonomous and automatically acting systems. At that level, systems will be able to make decisions by using the previously acquired and analyzed data, without the need for human assistance. [7]

A comparison of the OSA-CBM framework and the digitalization approach reveals multiple similarities. Both models are driven by the objective to acquire and analyze data of a system to understand its physical properties, to predict a future system state and to decide about efficient and enhanced utilization. However, the digitalization level of connectivity marks a big difference. The OSA-CBM approach does not clearly intend to connect the acquired data to external systems. The architecture of the new ACMS follows the step by step digitalization approach with the aim of an adaptable system, i.e. fully autonomous and automated. The paradigm of the OSA-CBM framework is covered by the exact implementation and content of the digitalization levels for the tire pressure inspection.

The presented digital transformation approach is divided subsequently into three steps. First, we investigate the current digitalization level of the present tire pressure inspection process. Second, we measure the gap between the current and the required digitalization level, i.e. adaptability. Third, we identify digital technologies which need to be implemented into the current process in order to achieve a higher digitalization level.

In this approach, we define the TPIS as the standard system in an aircraft. As described in section 2, the TPIS constantly measures and sends the pressure data of a tire to the ECAM system and also provides alerts for low tire pressure conditions. As it can be seen in Figure 3, the system itself is already on the transparency level, since system information is compared against given thresholds and evaluated. In contrast to the TPIS system, the tire pressure inspection process is not on the transparency level, since the data from the TPIS remains inside the closed-loop aircraft system without any transfer to external systems. The pressure data has to be manually obtained from the ECAM system in fixed time intervals. Hence, the TPIS is not connected to the overall process, it is only computerized. Figure 3 shows the different digitalization levels of the TPIS and the inspection process.

Especially when it comes to enhanced decision support for the tire maintenance, additional to the measured tire pressure, further data is required, e.g. brake and ambient temperatures for the generation of a temperature compensated tire pressure. The temperature information is available inside the aircraft system but is neither used by the TPIS nor connected to the overall inspection process.

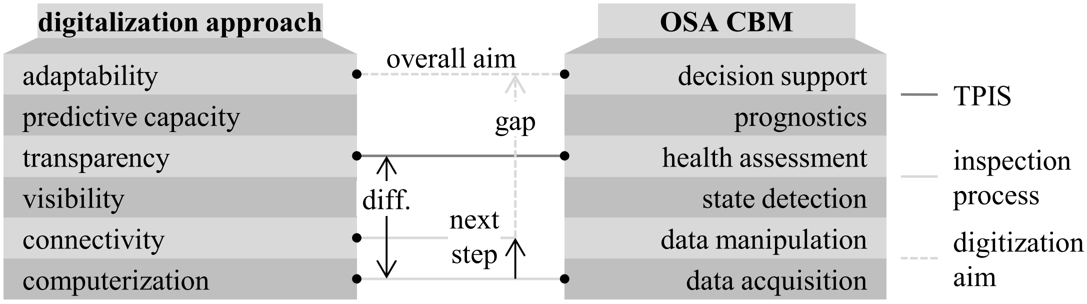

Figure 3: Digitalization Levels of the TPIS and the Tire Inspection Process

To reach the highest digitalization level, multiple steps are necessary. The first step is to transfer the pressure data from the TPIS and the temperature data from the aircraft to a superordinate system. This superordinate system could be a ground station, where data from different sources inside the aircraft is collected, further analyzed and made available. Accordingly, a technology to transfer the data to a ground station is required.

There are multiple technological possibilities for the transfer of digital data. These technologies can be divided into three groups: Wireless transmission, wired transmission and transmission by portable storage media. Based on the amount of data to be transferred, the transmission speed, and infrastructural effort, the wireless data transmission is the most suitable solution. In particular Wireless Local Area Network (WLAN) is an effective solution, due to the fact, that many aircraft already use WLAN for system updates and data exchange. Therefore, solutions for the integration of a digital connection technology are already available. [9]

With the implementation of a data transfer from the aircraft to the ground station, the connectivity level for the tire inspection process is reached. As shown in Figure 3, the next step is to further improve the process to the transparency level. Since the TPIS already has the ability of assessing the health status of a tire based on its pressure and, thus, is already at a transparency level system-wise, an inspection process with ground station connection will be on the same digitalization level. The following chapter investigates how this transparency can be used to reduce maintenance costs by analysing the pressure data to avoid unnecessary service and repair tasks. The last steps to achieve the overall ACMS goal are the implementation of a prediction system for the tire pressure and the automation of the decision support for the operation and execution of service and repair tasks.

4 NEW SYSTEM LAYOUT

To transfer the current tire pressure indicating system into a fully automated prognostic system, we develop a new system layout (ref. Figure 4) in this chapter. All necessary technical parts of the proposed system on the aircraft are already available. Thus, only interconnections between the TPIS and the Condition Monitoring System have to be established. To enable a diagnostic function, the information of tire pressure, air temperature and brake temperature will be transferred to a ground station once per flight cycle. We chose the two mentioned temperatures to account for possible changes of the tire pressure as a result of heat emission from the brakes during the landing process. Additionally, current aircraft are already equipped with adequate sensors to record the data.

As the best suitable time for a reliable measurement between two flights, we identified the moment when the first engine will be started. The tire's nitrogen temperature will most likely be closest to the ambient air temperature and associated measurements can clearly be identified within the aircraft systems' recordings. However, to reduce the risk for operational irregularities in case of an underinflated tire, a continuous measurement after landing for first indication should be considered. Furthermore, we expect measurements after night stops to deliver the most accurate pressure readings since temperature effects can be neglected as the nitrogen's temperature and the ambient air temperature will be nearly equal.

Within the digital representation of the aircraft's tires (digital twin), a normalization of the pressure data should be performed. This would include both, temperature compensation as well as data failure handling, e.g. rising pressure without repressurization tasks in between or missing records. For the state detection as part of the OSA-CBM model, the limits must be included into the digital twin either by original equipment manufacturer (OEM) data or aircraft maintenance manual (AMM) data.

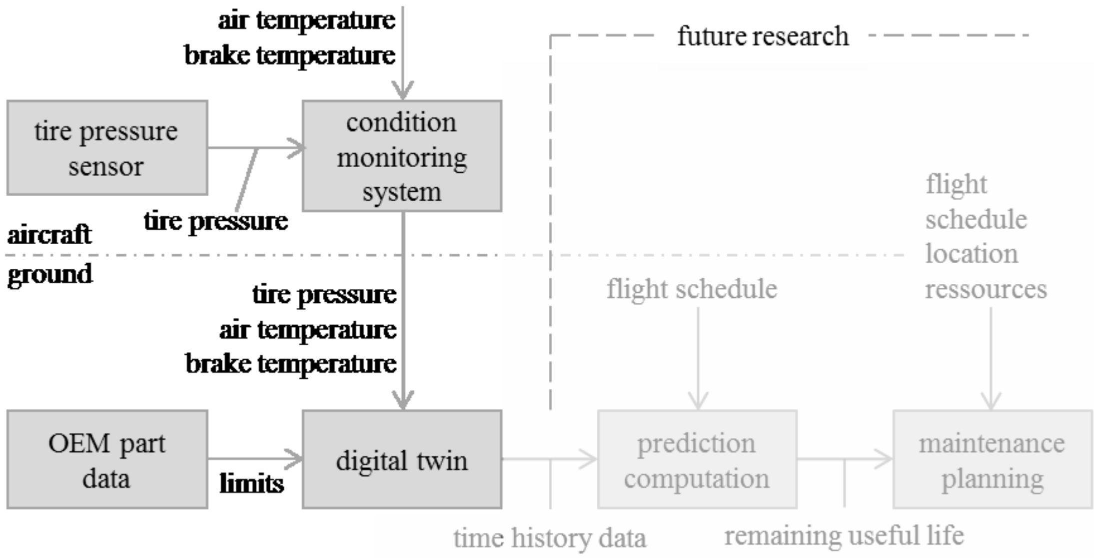

Figure 4: New System Layout

We will focus solely on a system design up to the digital representation of the TPIS and the calculation of cost benefits after implementation of such a maintenance approach compared to scheduled inspections. Further developments shall include information about the utilization, i.e. the flight schedule, and tire history, e.g. rethreading, to allow a precise prediction of upcoming maintenance needs and to enable a cost-benefit optimized maintenance planning. Thus, we expect the cost benefits to be even greater compared to the approach presented in this work.

5 PARAMETRIC STUDY

After the new system layout has been introduced, we will focus in this section on developing a simulation model to calculate its potential for reducing maintenance cost. For this study, we chose a daily utilization of 6 flights as an exemplary representation of a narrow body aircraft from a large European hub-and-spoke carrier [3]. The considered time frame for the simulation is one calendar year. Additionally, we assume that the conventional tire pressure checks will be conducted every 3 calendar days or 18 flight hours respectively, given the utilization and according to the MPD [2], and that a TPIS state-of-the-art system is installed on the aircraft. Due to the unavailability of real data, we simulated the pressure loss of the aircraft tire with the help of a normal distribution; left-truncated at a pressure of 0 bars with random daily pressure drops. We performed a Monte-Carlo simulation with 1,000 runs for each parameter combination to account for the effect of randomness and to yield viable results. Table 2 shows the cost structure associated with the tire maintenance.

Table 2: Overview of Assumed Cost for Tire Maintenance [10]

Position	**Description**	**Cost per Tire**
C_{Read}	Cost for pressure checks	\$3.34
$C_{Refill,unscheduled}$	Cost for unscheduled repressurization	\$120
$C_{Refill,scheduled}$	Cost for scheduled repressurization	\$120
$C_{Inspection}$	Cost for detailed tire inspection	\$240
$C_{Replace}$	Cost for tire replacement	\$1,400

According to the man-hours required for the pressure reading task given by the MPD [2], we estimated the associated costs C_{Read}, including necessary equipment, to be \$20 for all six tires of an A320 or \$3.34 per tire, respectively.

Once the pressure drops below the manufacturer's initial threshold and the tire needs to be repressurized, the associated labor and equipment costs are assumed to be \$120 for both, the conventional approach, $C_{Refill,unscheduled}$, and the continuously monitored approach, $C_{Refill,scheduled}$. Although in reality, a plannable refilling task is likely to cause lower associated costs, due to the proactive diagnosis and failure prediction and the resulting optimized assignment for the task, we do not consider any cost differences for unscheduled and scheduled events. After a further pressure loss below a second threshold, the tire needs a thorough inspection for structural damage, therefore causing additional labor cost and requiring specialized equipment.

The replacement of the wheel is necessary, once the pressure is surpassing another threshold without repressurization. Since the tire needs a detailed rework in the shop thereafter, the associated costs incorporate the wheel removal from the aircraft, tire retreading as well as the necessary labor and shipment costs [10]. Under specific circumstances, i.e. excessive differential pressure for tires on a single axis [6], it may be necessary to remove both wheels of that axis, therefore doubling the replacement costs.

6 RESULTS

After the methodology and the general simulation setting have been introduced in the previous chapter, in this chapter we focus on quantifying the operational impact in terms of maintenance cost reduction. In Figure 5 it is shown how the annual maintenance costs for one tire of an A320 aircraft vary between the conventional and preventive approach for various average daily pressure losses and standard deviations without taking the investment costs for the installation of a condition monitoring TPIS into account. Furthermore, we consider three different cases:

- The preventive maintenance threshold remains unchanged at the level of the conventional threshold. (Figure 5, left)
- The preventive maintenance threshold is lowered by half of the safety margin, i.e. to 97.5% of the conventional repressurization threshold. (Figure 5, middle)

- The preventive maintenance threshold is lowered to the minimum allowed pressure for simple repressurization tasks, i.e. to 95% of the conventional threshold. (Figure 5, right)

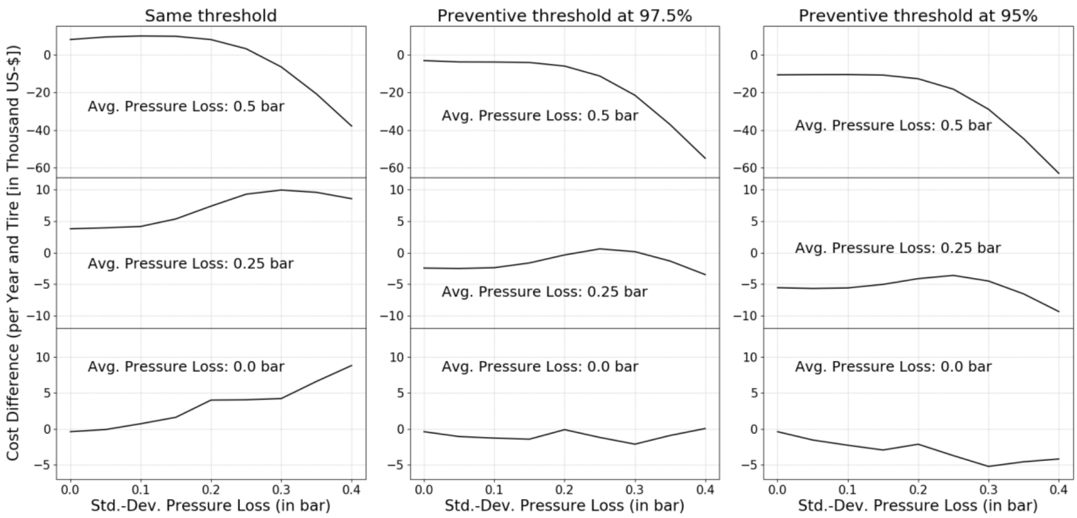

Figure 5: Cost difference ($C_{Prev} – C_{Conv}$) per tire and year

The cost saving potential for the continuously monitored system depends on the average pressure loss and the volatility of data. Furthermore, it appears that a continuously monitored system will not help to reduce maintenance costs, as long as the maintenance process itself will not be adapted accordingly. Since the current system accounts for an operation with undetected faults by the installation of safety margins, a continuously monitored system will lead to more maintenance tasks as faults will be detected at an earlier stage and, thus, rectified more often. Although this helps to avoid costly subsequent damages, i.e. detailed tire inspections or wheel replacements, for little daily pressure losses with little volatility the risk for this task to be necessary is negligible for the conventional approach as well due to the system's safety margin. For an unchanged maintenance approach, the investment cost for a continuously monitored system would therefore be unjustified in terms of overall cost savings.

To effectively reduce maintenance cost with an ACMS for tires, the maintenance threshold has to be lowered as the risk of undetected faults, i.e. pressure loss beyond the maintenance threshold, decreases with increasing capabilities in diagnosis and prognosis. This effect can be observed in Figure 5. For a maintenance threshold at 97.5% of the conventional threshold, a continuously monitored TPIS is already cost beneficial for almost all combinations of average pressure losses and data volatility compared to the conventional approach. The true potential of the proposed system is shown once the maintenance threshold will be lowered to 95% of the conventional maintenance threshold. According to [6], this pressure corresponds to the maintenance threshold where a repressurization will not be sufficient once the tire pressure drops below and, thus, would result in higher subsequent maintenance cost. This approach will lead to a significant cost reduction for all realistic daily pressure losses and data variations. Additionally, it can be observed that the cost saving potential increases with higher pressure losses and higher volatility. The reason behind is the avoidance of costly subsequent checks and repairs, thus limiting necessary maintenance almost exclusively to repressurization tasks.

Table 3 shows the maintenance cost saving potential per tire of a fully automated TPIS compared to the current approach for 3 different average daily pressure losses and different standard deviations. Since all the values represent the maintenance cost saving potential for one tire, the cost reduction for an A320 aircraft with a maintenance threshold lowered to 95% of the conventional threshold and an average daily pressure loss as well as standard deviation of 0.05 bars will roughly be $12,000 per year. With an average life time of 25 years [3], the total maintenance savings for the TPIS will be approximately $302,000. This value does not account for operational impacts of such a system. Therefore, savings by reducing flight cancellations or delays as well as reducing necessary replacement inventory need to be added on top of it.

Table 3: Calculation of Maintenance Cost Difference per Tire and Year

Mean daily pressure loss	Std.-dev. pressure loss	Cost difference between preventive and conventional approach (C_{prev} - C_{conv})		
		Same maintenance threshold	*Maintenance threshold lowered to 97.5%*	*Maintenance threshold lowered to 95%*
0.05 bar	0.05 bar	$269	$ -1,217	$ -2,016
0.15 bar	0.15 bar	$1,535	$ -1,274	$ -2,882
0.25 bar	0.25 bar	$3,048	$ -1,915	$ -5,243

In general, we identified that the cost saving potential of a condition monitored system is driven mainly by the following factors:

- The variation of the maintenance threshold for the continuously monitored system compared to a conventional system – The benefits of an automated, continuously monitored system increase with a difference in maintenance thresholds, as a result of reduced safety margins.
- The time span between regular, conventional inspection tasks – A greater time span between inspections usually leads to higher safety margins, but also to a higher risk for undetected faults to cause costly subsequent damages.
- The penalty costs for subsequent repair tasks – These penalty costs can incorporate both, the cost for repair or additional inspections and operational implications, e.g. a larger inventory for replacement parts or irregularities due to longer rectification times.

7 CONCLUSION AND OUTLOOK

In this paper, we presented an estimation of potential maintenance cost savings with the implementation of an ACMS for tires of an A320. For all operating aircraft of the A320 family in Europe the annual time saving potential for a routine scheduled tire pressure reading task equals 26,000 MH by installation of an automated system. Additionally, the digitalization potential for the TPIS has been analyzed with the help of the OSA-CBM model, showing the required digitalization steps and technologies in order to achieve an ACMS for the tire inspection process. It has been compiled that the next digitalization step is to achieve connectivity between data inside the aircraft system and an external ground station for further data analysis. We further proposed a schematic layout for an automated TPIS based on the state-of-the-art technology. For a first improvement of the current system, the TPIS needs to be equipped with technical possibilities to transfer and store measurement data, thus, enabling the representation of the system in a digital twin. By having historical data for the aircraft specific TPIS available, it will be possible to carry out trend analyses and smart diagnostics. In a second evolution, in order to develop prognostic capabilities, we suggested the combination of historical data with the expected utilization, i.e. the flight plan.

By implementing a continuously monitored TPIS, we could identify the maintenance cost saving potential as a result of eliminating repetitive check tasks as well as avoiding costly subsequent maintenance tasks. We calculated the total maintenance cost reduction for an A320 after installation of the proposed TPIS to be $12,000 per aircraft and year. For a large hub-and-spoke network-carrier with 130 narrow-body aircraft, this would equal $1.56 Million per year. These savings do solely consider reductions in maintenance costs. Thus, operational benefits resulting from the implementation will be added to that, e.g. less flight delays and cancellation or a reduced inventory stock.

Since the work we presented in this paper focused on the elimination of unnecessary tasks by continuously monitoring the tire pressure, future work should include maintenance improvements by enabling failure prognostics based on the planned aircraft's utilization according to the flight plan. The prognosis of upcoming failures will allow an optimized allocation of tire maintenance activities and, thus, help to reduce maintenance costs even further. Additionally, we assumed for this paper the unrestricted availability of measurement data. In reality, the restrictions given by the MPD and the manufacturer's instruction pose an additional challenge in developing a condition monitoring system for reliable data acquisition. Therefore, it needs to be determined how the forecast precision changes with the frequency of acquired tire pressure information. The trade-off needs to account for additional investment costs for a temperature compensated tire pressure and the gained precision with measurement after every flight.

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