Assessing cyber-physical systems to balance maintenance replacement policies and optimise long-run average costs for aircraft assets

Marco Andreacchio, Abdelghani Bekrar, Rachid Benmansour, Damien Trentesaux

IET Cyber-Physical Systems: Theory & Applications

Research Article

IET Journals
The Institution of Engineering and Technology

Assessing cyber-physical systems to balance maintenance replacement policies and optimise long-run average costs for aircraft assets

ISSN 2398-3396
Received on 10th September 2017
Revised 10th July 2018
Accepted on 26th October 2018
E-First on 9th January 2019
doi: 10.1049/iet-cps.2018.5038
www.ietdl.org

Marco Andreacchio[1] ✉, *Abdelghani Bekrar*[2,3], *Rachid Benmansour*[2], *Damien Trentesaux*[2,3]

[1]*EAM RFID Solutions (subdivision of EAM Worldwide), 5502 NW 37th Avenue, Miami, Florida 33142, USA*

[2]*LAMIH UMR CNRS 8201, Polytechnic University Hauts-de-France, Le Mont Houy, F-59313 Valenciennes Cedex 9, France*

[3]*Surferlab, Distributed Intelligence for Transportation Systems Laboratory, Polytechnic University Hauts-de-France, Le Mont Houy, F-59313 Valenciennes Cedex 9, France*

✉ *E-mail: marco.andreacchio@eamrfid.com*

Abstract: Many aircraft assets are subject to both preventive (scheduled) and corrective (unscheduled) replacement policies to ensure adequate levels of reliability and availability. The problem, particularly for assets that exist in large quantities, is that preventive replacement tasks often involve removing the entire population of assets from the aircraft, regardless of whether any assets were previously replaced on a corrective basis beforehand. To avoid the costs associated with premature asset removal, this study assesses the use of a cyber-physical systems approach to the management of identified aircraft assets. This approach builds on an industrial architecture that has been implemented and deployed in the aviation maintenance environment. This study outlines how the cyber-physical based identification of assets can facilitate balancing maintenance replacement policies to optimise long-run average costs per unit time. A mathematical model is proposed, and the suggested approach is validated using industrial data.

1 Introduction

The air transportation industry is characterised by high-fixed costs and low-profit margins [1]. Aircraft maintenance is a vital yet expensive function, and on average, it represents ∼12% of the total operating costs of an airline [2]. Maintenance, repair, and overhaul (MRO) must maximise aircraft availability, operability, and item-level reliability [3] to maintain a competitive advantage.

However, for every dollar spent on aircraft maintenance on average, airlines still continue to hold approximately one dollar of spares and inventory [4]. This storage is arguably excessive. As a result, there is continuous interest in devising maintenance policies that improve inventory management and better use of aircraft assets during maintenance checks. In this paper, we consider assets characterised by a large number of identical replaceable elements inside each aircraft, such as seat covers, floor panels, insulation blankets, curtains, linens, and emergency equipment such as life vests. Whether to replace one or more of these items must be determined periodically. For these assets, a cyber-physical system (CPS) solution that, at the minimum, identifies, precisely locates, and contains the past history of every asset may facilitate balancing preventive and corrective maintenance tasks. Such an implementation may enable better asset utilisation (where possible) and reduce long-term replacement costs. Initial ideas presented in Andreacchio *et al*. [5] are extended in this paper, particularly in terms of the mathematical formulation and case study experiments. Moreover, a feasibility study on the deployment of a CPS is also discussed herein. To understand the benefits of such an approach, two tentative mathematical models are thus suggested that will assist in quantifying the costs associated with manual corrective and preventive replacement tasks and the savings associated with implementing a CPS.

A case study will be presented in this paper with respect to aircraft passenger seat covers (a specific, important aircraft cabin asset) using real industrial data from an airliner. Aircraft passenger seat covers (referred to as upholstery in Fig. 1) are designed to protect the seat cushion from accidental or deliberate wear and tear. This asset was chosen because seat covers are considered 'high churn' items [6] that are often subject to costly routine and periodic replacements through both preventive (scheduled) and corrective (unscheduled) maintenance. The case study will draw on numerical data obtained from industrial interviews and on a mathematical model to present the benefits of future CPS implementation.

The paper is organised as follows. First, the problem statement is outlined, followed by an industrial and academic literature review. A CPS-based architecture is proposed along with the numerical data and mathematically based models. The results and analysis are presented and then validated.

2 Problem statement

The quality of interior assets, such as cabin furnishings, depends on aircraft utilisation [7]. Airlines that operate aircraft with relatively high flight hours and more cycles allocate considerable resources to maintaining cabin appearance, including the changeover of these assets. Aircraft maintenance checks are scheduled and packaged in a variety of ways and are generally referred to as an A-checks, C-checks, or D-checks. 'A-checks' may be scheduled every 500 to 600 flight hours. 'C-checks' are more intense and are performed approximately every 6000 flight hours, or every 24 months [8]. 'D-Checks' are much less frequent. During these checks, a range of corrective and preventive maintenance activities may be performed that require a varying amount of ground time to complete.

Corrective maintenance is reactionary. It occurs on an unscheduled basis, and constitutes the repair or replacement of an asset after a defected fault has occurred. Corrective maintenance is generally conducted after the failure of an aircraft asset with the objective of restoring the aircraft to a functioning state as soon as possible, either by repair or replacement [9].

Preventive maintenance, in contrast, occurs on a scheduled basis [3] and is intended to reduce the probability of asset failure or degradation. Preventive maintenance in this sense is performed under the assumption that assets have a defined expected life span or measurable degradation [10], after which they must be replaced.

Aircraft assets are subject to various forms of preventive or corrective maintenance. Indeed, many assets, particularly aircraft

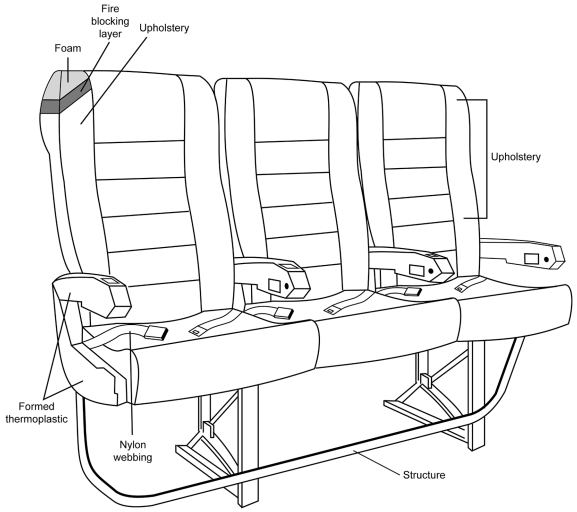

Fig. 1 *Aircraft seat covers*

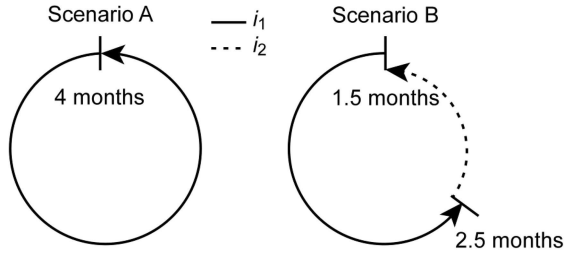

Fig. 2 *Graphical depiction of an asset replacement cycle*

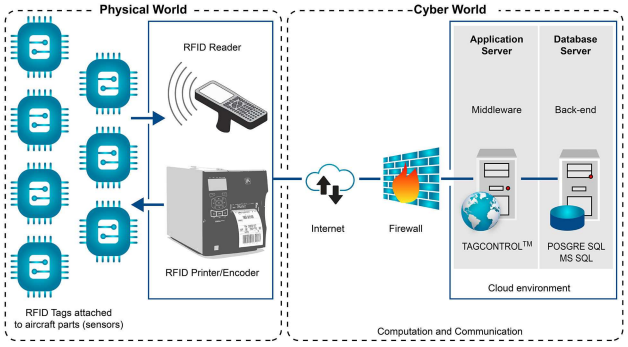

Fig. 3 *Basic system architecture of TagControl™*

cabin furnishings, require both condition-based and time-based replacements, meaning that corrective and preventive maintenance regimes are simultaneously applicable. The problem is that between two preventive replacement tasks, an individual asset may undergo a corrective replacement. When this is the case, the next scheduled preventive replacement task may not necessarily take into account whether that asset has been changed on a corrective basis shortly before the preventive replacement task.

For example, Scenario A in Fig. 2 depicts a particular asset (referred to as i_1) that requires a scheduled preventive replacement. Here, a 4-month preventive replacement interval ($T=4$) is shown with no corrective replacements required. In Scenario B, the same asset i_1 undergoes a failure event after 2.5 months and requires immediate unscheduled corrective replacement. This replaced asset (referred to as i_2) was installed for only 1.5 months before being replaced again at the 4-month ($T=4$) preventive inspection interval corresponding to the original installation date of i_1. Assuming the asset in Scenario B has a maximum overhaul limit, then its premature removal results in costs associated with underutilisation.

The problem addressed in this paper is as follows: considering a CPS-based approach that enables us to identify and manage the history of each aircraft asset, how can we optimise the balance between the preventive and corrective replacement of these aircraft assets and optimise relevant long-term costs? Before presenting our approach, a short review of the academic and industrial research in this context is provided.

3 Industrial and academic literature review

The literature on maintenance policies has been surveyed [11] in the context of stochastic failures [12], deteriorating systems [13], and optimizing preventive maintenance and corrective maintenance [14–17]. However, the aircraft maintenance industry continues to rely on manual, paper-based processes that are highly inefficient and can result in data mishandling [18–21].

Advancements have been made with the conceptualisation of future industrial systems, specifically Industry 4.0, internet of things [5, 22], and CPS technologies. CPSs enable a convergence of the virtual and physical worlds by creating a networked reality in which intelligent objects communicate and interact with each other. They integrate computational and physical processes [23] consisting of sensors (or actuators) combined with computation and communication. CPSs have been considered and proposed [24, 25] in multi-agent, [26] manufacturing [27, 28], and medical [29] contexts.

Radio frequency identification (RFID) systems consist of RFID tags, readers, and a back-end system to analyse the data of the scanned tags. RFID technologies have been implemented to achieve efficiencies throughout the supply chain [30–34] and have been shown to improve the speed and efficiency of aircraft maintenance inspections [35–41]. Indeed, RFID systems have the potential to play a role in enabling self-serving assets [42, 43] to improve the dynamic information flow of aircraft assets.

Particular attention has been given to the potential benefits of integrating CPS in the aircraft maintenance environment [44–49]. When networked together, an RFID based system can be considered a CPS [50].

EAM Worldwide is a major manufacturer of life vests, life rafts, and other survival equipment for commercial airlines. EAM Worldwide has manufactured more than two million life vests with embedded RFID tags; the RFID tags can be scanned for the purposes of onboard inspection. Fig. 3 below outlines the architecture based on the RFID technology that was developed by EAM Worldwide's RFID division. This system (entitled TagControl™) has been implemented and is currently in use with several major airlines (such as Fiji Airways) and MRO operators. TagControl™ specifically tracks aircraft assets inside the cabin during maintenance inspections.

TagControl™ integrates sensor-based technologies (such as RFID tags) on individual aircraft assets, turning them into 'intelligent assets'. Using an RFID reader, maintenance engineers can perform scans on the tagged assets. The system has the capability to independently connect, trigger, and assist with the maintenance scheduling of the assets using a range of automated reporting functions. This scheduling is based on the asset's shelf life and other onboard maintenance requirements.

RFID sensor technology can be seen as an appropriate first step for full CPS implementation because RFID tags are permitted to be fitted to assets inside aircraft [51–53]. The data encoding is also approved [54] for RFID tags in the aviation industry, as illustrated in the review section. Meanwhile, this actual solution faces some issues. For example, the use of an RFID-tag handheld reader limits the reactivity of the system since data synchronisation with the central databases is not automatic and, thus, not immediate. Moreover, another key challenge that may manifest itself is ensuring data integrity. This challenge is important as the data may be safety critical.

From this review, we suggest that adopting a CPS approach would go a step beyond RFID-based solutions and would facilitate the balance between corrective and predictive maintenance policies; however, optimizing this balance and the associated long-term cost remains to be studied. Clearly, to achieve this, integration is required with the maintenance information system (MIS) of the airline, and the following discussion provides more specificity for this proposal before its assessment.

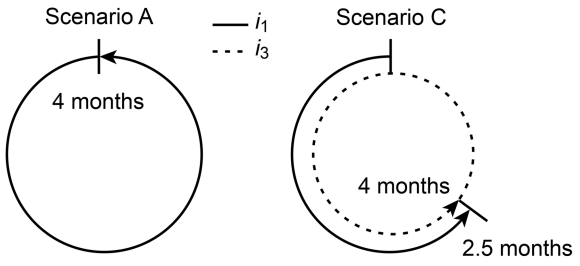

Fig. 4 *Graphical depiction of a CPS-based asset replacement cycle*

4 Specifying the use of CPS to balance preventive and corrective replacement policies

Under our proposal, each asset first needs an individual sensor with a unique identification tag that enable it to become an active cyber-physical part of a much larger CPS system. As an active cyber-physical part, an asset would be able to trigger a maintenance alarm, e.g. instead of waiting to be read. Moreover, the sensor would communicate data via a series of interrogators (as opposed to using a handheld reader, such as in classical RFID-based solutions) and then relay that information directly to the MIS. This would enable real-time configuration data to be transmitted to the MIS, enabling tasks to be scheduled based on a more accurate picture of the aircraft's configuration. Maintenance engineers would know exactly which asset to replace when the task is scheduled. More importantly, due to the real-time nature of this proposal, assets would be able to digitally align their corrective or preventive replacement automatically and schedule this replacement through the airline MIS, possibly through negotiation with other assets of the same aircraft (e.g. group triggering thresholds instead of single asset triggering) or even with other assets of the same third-party repair organisation. Opportunistic or dynamic maintenance operations could also be identified by this approach, achieving dynamic adaptation of the predictive maintenance period based on the history of the 'swarm' of intelligent assets [45].

In our proposal, when an identified asset is installed at a location during a replacement task, the asset is assigned to the location with a timestamp. Then, during the next maintenance task (whether it be preventive or corrective), the onboard interrogators can identify the timestamp of each asset's installation. By doing so, the MIS can compute whether each asset has enough life to continue to the next scheduled replacement task based on the maximum permissible onboard life. This means that during the preventive replacement task, maintenance personnel would be required to replace only the assets for which the remaining permissible onboard life is less than the preventive replacement inspection interval. Other assets that were replaced more recently due to corrective replacement would not be unnecessarily removed.

By implementing this type of CPS, both corrective and preventive replacement tasks can then be integrated.

As an illustration, in Fig. 4, Scenario A once again illustrates a normal aircraft asset (referred to as i_1) subject to a preventive inspection interval of 4 months with no corrective replacements. In Scenario C, the CPS-enabled asset encounters a failure event after 2.5 months, and the preventive 4-month ($T = 4$) scheduled interval is reset to the date of installation of the asset i_3.

Although the focus of this discussion is a single asset, important long-term benefits could emerge from integrating cooperative behaviors, as previously explained.

From these specifications, several scientific issues remain to be solved to ensure the feasibility of the suggested CPS approach. In this paper, we suggest answers to the following questions:

- As a result of the reduced time for performing the preventive check using CPS, to what extent can the preventive replacement interval be adapted?
- If the probability distribution of corrective replacements is known for a given time period, how can the benefits of the CPS due to increased asset utilisation be assessed?

To answer these questions, a numerical scenario model and mathematical models have been developed and are presented in Section 5.

5 Numerical scenario and mathematical models

To determine the ideal CPS-based maintenance policy for the asset management problem, we propose and articulate two models. The first model is numerical and scenario-based, inspired by the state-of-the-art generalised age and block replacement models. Detailed comparisons of age and block replacement policies can be found in early [55–57] and more recent [5] literature.

The second model is a mathematically based framework aimed at balancing the preventive and corrective maintenance costs of the assets.

The objective for using these models is to show the importance of balancing between corrective and preventive maintenance.

5.1 Assumptions and parameters of the models

We consider only one type of asset. We also assume that the preventive and corrective costs for an asset, as well as the failure rate for an asset, are constant. The parameters used in this paper are the following:

c_p constant cost of preventive replacement of asset
$c_p(i, t)$ preventive replacement cost of asset i at period t
c_s constant cost of corrective replacement of asset
$c_s(i, t)$ corrective replacement cost of asset i at period t
T cycle time – periodicity of preventive maintenance
α rate of change of assets by maintenance in a cycle

5.2 Numerical, scenario-based model

The goal of this model is to determine the optimal policy and optimal starting value of cycle time T that will be adopted when implementing the CPS. For this first model, we study two concurrent policies: block replacement and age replacement.

5.2.1 Block replacement policy: For the block replacement case, the preventive replacement interval occurs every T units of time (T is illustrated in Fig. 2). This replacement policy is based on the notion of replacing a 'block' or 'group' of units in a system at routine intervals, regardless of the failure history of that system. In other words, under the block replacement policy, an asset is replaced at predetermined fixed times $k \cdot T$ (T, $2T$, $3T$, …).

Under the block replacement policy, two types of replacements are conducted:

i. Assets as they fail (in-service failures, sometimes called 'emergency replacement')
ii. All assets (regardless of which have failed and been replaced, sometimes also called 'planned failures') at fixed times ($k \cdot T$).

In this model, we assume that $c_s > c_p$, and the objective is to find the condition under which this inequality enables us to determine an optimal cycle time T. The main benefit of block replacement policies is the simplicity of these policies since keeping specific records on individual assets is unnecessary. Furthermore, block replacement policies can be applied to large batches of assets, thereby achieving economies of scale. While the administration cost for block replacement policies is lower, the policy results in more waste than the age replacement policy, since an asset might be replaced periodically. In our numerical scenario, we also considered a gamma function with an increasing failure rate, for which the probability density function is given by (see [58])

$$f(t) = \lambda^2 t\, e^{-\lambda t}$$

where λ is a scale parameter of the gamma function.

In that case, the first moment (mean) is

$$\mu = \frac{2}{\lambda}$$

The renewal function, $M(t)$, defines the expected number of failures, $N(t)$, in an interval [0, t] as (for more details, see [58])

$$M(t) = E(N(t)) = \frac{\lambda t}{2} - \frac{1}{4}(1 - e^{-2\lambda t})$$

The mean cost incurred per cycle of length T per unit time is given by

$$C(T) = \frac{c_p + c_s M(T)}{T}$$

Therefore, on average, and during one cycle of duration T, we pay a cost of preventive maintenance c_p only once and we pay the cost c_s of the corrective maintenance $M(T)$ times.

To find the optimal cycle T, the differentiation with respect to T and set to zero, gives

$$e^{-2\lambda t}(2\lambda t + 1) = 1 - 4\frac{c_p}{c_s}$$

This equation has a unique solution T provided that

$$c_s > 4c_p \tag{1}$$

which was the information we were seeking.

5.2.2 Age replacement policy: One of the main benefits of the block replacement policy is the ease of management of large asset quantities since asset replacement records do not have to be kept. In the block replacement policy, all assets are replaced at time $k \cdot T$, regardless of the length of time in service. The inherent disadvantage is that almost new assets (those replaced upon failure just before time $k \cdot T$) are replaced at planned time $k \cdot T$. Instead, in age replacement policy, assets may be replaced at a constant predetermined age T or upon failure if it occurs earlier [55]. Preventive replacement of the asset is conducted once the age of the asset has reached a specific/critical operational age. This approach is widely used, and specific details of the age replacement policy can be found in [58, 59]. The age replacement model is well suited to bounded assets (i.e. regulated for public safety) for which fixed replacement time intervals are mandated or typical age-based renewals. With this background in mind, the mean cost incurred per cycle of length T per unit time is given by (see [58])

$$C(T) = \frac{c_s - (c_s - c_p)R(T)}{\int_0^T R(x)\,\mathrm{d}x}$$

where $R(t)$ is the reliability function.

We use the same gamma function defined in Section 5.2.1 to find the optimal cycle T for this strategy. Hence we differentiate $C(T)$ with respect to T and set the result to zero ([58]):

$$e^{-\lambda t} = \frac{c_s}{c_s - c_p} + \left(\frac{c_s}{c_s - c_p} - 2\right)\lambda t$$

This equation has a unique solution if and only if

$$2c_p < c_s \tag{2}$$

which was the information we were seeking. The optimality of this policy was demonstrated in [60] if the replacement by a new item is the only maintenance option. In the present problem, it is not possible to repair an item while the aircraft is grounded; defective items must be sent to a special centre for repair.

5.3 Mathematical model

The suggested CPSs may precipitate rescheduling the associated replacement tasks from the installation dates of the assets on the aircraft. This section contains a first modeling attempt aimed at understanding the benefits of implementing such a system. This model is currently high level and implementing it in a real-time context is complicated due to computational constraints. However, it is interesting to validate this mathematical model to provide first results before using the CPS-based maintenance. The model exploits the initial T cycle determined by the previously described numerical scenario model (by age or block policy) and evaluates whether it would be useful for it to become dynamic, assuming that the CPS-based architecture enables this evolution. This model considers two main decisions: when preventive maintenance and corrective maintenance are launched. The balance between the two is based on the costs associated with each of them.

5.3.1 Variables, constraints, and objective function of the mathematical model:

X (i, t) Binary variable equal to 1 if the asset i is changed by preventive maintenance at period t
Y (i, t) Binary variable equal to 1 if the asset i is changed by corrective maintenance at period t

The constraints are the following. First, the total use of asset i should be less than or equal to the maximum use (MaxU):

$$\sum_{i,t} [X(i,t) + Y(i,t)] \leq MaxU$$

When preventive replacement for asset i occurs at period t, the next preventive replacements are launched at periods $t + k.T$, which is formulated as follows:

$$X(i,t) = 1 \text{ then } X(i, t+T) = 1, X(i, 2.t) = 1, \ \ldots$$

Second, when corrective replacement for asset i occurs at period t, $Y(i,t) = 1$, and when the rate α is reached, the next preventive campaign may be postponed for a period proportional to this rate:

$$X(i, t + \alpha T) = 1, \quad \alpha \geq 1$$

As introduced, this model tests the possibility for the cycle time (i.e. the preventive maintenance period) to be dynamic (which means that T changes over time because of α and corrective maintenance). The aim is to reduce the total maintenance cost based on both preventive and corrective maintenance decisions.

Therefore, the objective function can be expressed as

$$\text{Min} \sum c_p(i,t) \cdot X(i,t) + c_s(i,t) \cdot Y(i,t)$$

6 Application to aircraft passenger seat covers

Passenger seat covers are a kind of specific, critical asset that were discussed in Section 1. Cabin cleanliness is increasingly seen as a competitive differentiator between airlines, and this target includes passenger seat covers. A recent survey indicated that travelers are increasingly judging their air travel experience based on cabin cleanliness. In the survey, 82% of customers rated cleanliness as an important factor in subsequent re-purchase decisions [61].

Replacing aircraft passenger seat covers on a corrective (unscheduled) basis is required if a particular cover has been soiled or damaged during a flight. If a seat cover has been soiled and it is not replaced, then the seat may not be sold for the next flight segment.

Aircraft passenger seat cover assemblies consist of several sub-components, including seat bases, lumbars, shoulders, ears, and back pockets. Certain seat cover sub-components may require more frequent replacements and may have different scheduling requirements. For example, the base may require more frequent corrective replacements than the headrest, as the base may become

Table 1 Numerical scenario of the results for the block replacement model

Value of $1-4\frac{Cp}{Cs}$	Value of $2\lambda T$	T, days
0.1	3.88	58.2
0.2	2.994	44.91
0.4	2.022	30.33
0.6	1.376	20.64
0.8	0.824	12.36
0.9	0.5318	7.977

Table 2 Numerical scenario of results for the age replacement model

Value of $\frac{Cs}{Cs-Cp}$	T, days
1.1	18.933
1.4	64.095
1.6	118.56
1.8	269.97
1.9	570

soiled or marked more frequently. Corrective seat cover replacements are relatively non-labor-intensive (as such replacement may pertain to one or two seats per flight), and therefore, corrective replacements can be performed during downtime during the flight day or between flight cycles.

Aircraft passenger seat covers are subject to wear and tear that degrades the overall appearance of the cabin over time. A preventive time-based replacement task is often scheduled to ensure that the appearance of all seat covers meets a consistent minimum condition required for acceptable cabin presentation. Airlines specify an acceptable maximum time span for which a seat cover is permitted to remain on the aircraft, and all seat covers are removed from the aircraft and replaced at scheduled intervals.

A preventive seat cover replacement task for a Boeing 737 requires ∼50–80 person-hours for fabric covers [7, 8] and 100 person-hours for leather seat covers [7]. During this procedure, all the seat covers are removed from the aircraft and replaced with new ones. For example, Turkish Airlines removes, refurbishes, and re-installs seat covers on a preventive basis every 2 to 3 months to keep the cabin looking fresh and clean [7]. The costs are even higher for larger aircraft: the one-time removal of all seat covers as a preventive replacement task on a B747-400 costs ∼$23,000 [62]. Due to the large number of person-hours required to remove and replace all seat covers at once, the process of changing seat covers on a preventive basis is often aligned with a line or base maintenance check such as an A-check [8] or C-check. While the preventive replacement interval is relatively infrequent, it is not uncommon for corrective replacements to occur daily (between flights), particularly for larger airlines.

Seat covers are installed in the aircraft either on a corrective or preventive basis. The problem with the current status quo is that, as introduced in the review, seat covers are assets for which there is little visibility into the installation dates on an individual basis. The preventive time-based replacement therefore specifies that all seat covers should be changed. This requirement yields proportionally high costs for stripping off the seat cover, processing it, and washing it unnecessarily.

Aircraft passenger seat covers also have a finite number of times they can be washed. International standards regulate protection against fire onboard the aircraft, and certain materials installed in the aircraft cabin must meet flammability criteria prescribed by the Federal Aviation Administration, including aircraft interior seat cushions and upholstery [63]. Aircraft passenger seat covers contain a fire retardant to meet flammability requirements, and this fire retardant degrades proportionally with the number of times that it has been washed or dry-cleaned. As a result, many aircraft passenger seat covers are often permitted to be dry-cleaned only a finite number of times (as specified by the seat cover manufacturer); once they have reached the maximum number of wash cycles, they must be discarded [62]. Therefore, early (or premature) removal of a seat cover from an aircraft cabin decreases its usable life, representing an underutilisation cost. This section details the application of our proposal to the specific case of Airbus A380 seats.

As a reminder, the goal is to understand the conditions under which a CPS approach is viable for these assets. The real parameter values are confidential and cannot be provided in this paper. As a consequence, the parameter values used in this paper are not the exact values but approximated ones from real data obtained from industrial databases and interviews conducted with experts in the field.

6.1 Numerical scenario using a block replacement policy

We set the scale parameter λ of the gamma distribution to be 0.03333333, which is equivalent to a 2-month replacement cycle for block replacements and represents the industry norm.

With respect to Table 1, the optimal period of T varies from 7.97 days to 58.2 days. In the first case

$$c_s = 40c_p$$

In the second case

$$c_s = 4.4c_p$$

These calculations determine the optimal periodicity that minimises the overall long-term cost provided that the cost of corrective maintenance is proportional to the cost of preventive maintenance.

This result means that it is preferable to perform preventive maintenance as late as possible if the cost of corrective maintenance is negligible.

6.2 Numerical scenario using an age replacement policy

With respect to Table 2, the optimal period of T varies from 18.9 to 570 days. In the first case

$$c_s = 11c_p$$

and in the second case

$$c_s = 2.11c_p$$

Similarly, this strategy specifies the periodicity of preventive maintenance for values that respect (2). In the same way the periodicity increases if the cost of the corrective maintenance is low compared to the cost of the preventive maintenance.

6.3 Mathematical models

The mathematical models were implemented with CPLEX using concert technology (using C++) with the branch and cut algorithm [64]. The models are based on the following randomly generated data adapted from the previously introduced industrial data. First, c_p is randomly generated in the interval [100, 1000]. Then, c_s is defined as a multiple of c_p. We can set $c_s = m \cdot c_p$, where m is randomly generated in the interval [2, 40]. Finally, the rate α is randomly generated in the interval [1, 2].

To validate the mathematical models, Table 3 presents different scenarios based on the results obtained by the numerical scenario approaches. The first scenario is given as an example to compare the cost obtained by different approaches. Scenarios 2 and 3 are adapted from the block strategy, and Scenarios 4 and 5 are adapted from the age strategy. For each scenario, different disruptions are assumed to have occurred at different times for different assets. For example, ⟨1 9⟩ indicates a disruption occurred during period 9 for asset 1, requiring a corrective maintenance. The disruptions are generated randomly from real data to include different possibilities.

Table 3 Total cost table

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
number of seats	20	20	20	20	20
c_p	100	100	100	100	100
c_s	4000	4000	440	1100	225
number of periods	17	365	365	365	365
T	8	8	58	19	270
disruptions	⟨1 9⟩, ⟨2 3⟩, ⟨10 8⟩ ⟨14 3⟩, ⟨18 30⟩	⟨10 9⟩, ⟨12 3⟩, ⟨10 18⟩	⟨10 9⟩, ⟨12 3⟩, ⟨10 18⟩ ⟨14 3⟩, ⟨18 30⟩	same as scenario 3	same as scenario 3
total cost with model	13,800	107,700	12,200	41,400	1125

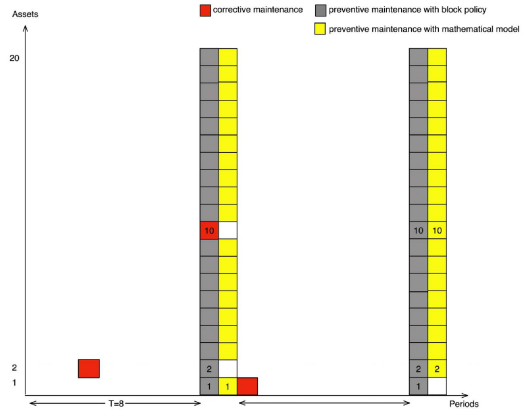

Fig. 5 *Comparing block policy and mathematical model for a simple scenario (no. 1)*

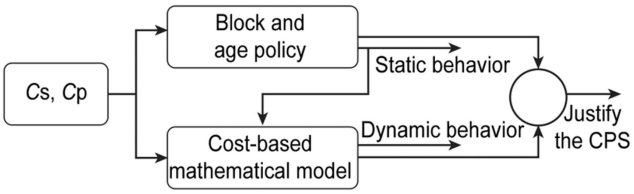

Fig. 6 *Relative positioning of the two suggested methods*

In the first scenario, to compare with the block policy, we consider a horizon with 17 periods (days). The optimal cycle time given by the block strategy is 8 days. The cost obtained with this solution is equal to \$14,000 on average ($2c_p \times 20$ seats $+ 3c_s$). Thus, the mathematical models predict an increase in preventive cost. When problems occur with seats 1, 2 and 10, the model proposes to postpone the preventive maintenance until the next period (see Fig. 5).

This simple example shows the utility of the mathematical models, which combines preventive and corrective maintenance and extends the preventive interval when possible. Under the condition for this first scenario, applying the introduced CPS solution for balanced preventive and corrective maintenance is viable.

For the other scenarios, when the cost of corrective maintenance is close to the preventive cost, it is beneficial to increase the maintenance interval (large T). However, when the corrective maintenance cost is much higher than the preventive cost, it is beneficial to specify more maintenance (small T), reducing the benefit of applying a CPS solution. These two approaches are complementary. The relationship between them is shown in Fig. 6

In this figure, the block and age strategies are considered to have static behavior, i.e. the cycle time is fixed. Conversely, the mathematical models can be used for dynamic behavior, for which the maintenance cycle time can be adapted to the situation. Each approach has advantages and disadvantages; however, both support the case for using CPS to balance corrective and preventive maintenance tasks.

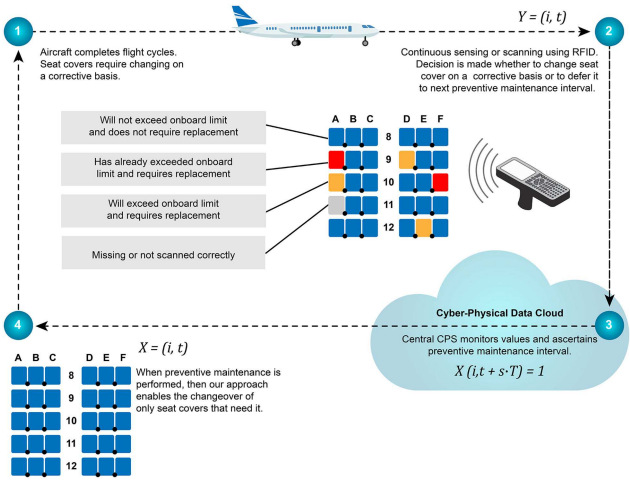

Fig. 7 *Implementation diagram of the first stage towards the deployment of a complete CPS approach*

7 Implementing our proposal: a first step

It is not within the scope of this paper to propose a fully operational CPS architecture that can be used by industrial partners. This process is quite complex and must be built iteratively from the initial situation to a fully developed CPS. Nonetheless, the first elements regarding the possible 'first-stage' implementation of the proposed CPS approach is depicted in Fig. 7, and is based on the current technology used by industrial partners but expanded to include seat covers.

In this figure, passive (single-record or dual-record) GS1 UHF spectrum RFID tags are attached to each aircraft asset. The encoding standard adheres to common industry standards as outlined in the ATA Spec2000, Chapter 9-5. The parameters encoded into the tag include the part number, serial number, manufacturer's CAGE code, and the date of manufacture.

Once the RFID tags are attached to each asset, the asset must be 'paired' with a unique location inside the aircraft. This means that each RFID-enabled asset must be manually assigned a unique location so that when the tags are scanned in bulk, they are identified with a pre-assigned aircraft location. In the first evolution of this architecture towards a full CPS, the system will have to be able to automatically determine the locations of the RFID-enabled assets (i.e. localisation); this process is currently not feasible. However, this capability may become possible in the future as new technologies become available and as we move toward full CPS deployment.

The initial 'assign' task (the task of assigning each RFID tag to a unique location) is a one-time task; based on industrial interviews and time trials, this task should take ~30 min for a Boeing 737.

Once the assign task is complete, the user submits the data (location, part numbers, serial numbers, wash count cycle and any other relevant parameters) to the cloud. The RFID reader then clears the data from the local database. During subsequent scanning inside the aircraft, the system will download the applicable aircraft registration with assignments, perform the scan and then upload the data again.

As stated previously, passive RFID tags do not have localisation ability and are passive elements that are waiting to be read. Transforming passive assets into active ones using the suggested CPS approach should allow the intelligent aircraft assets to determine their location within the aircraft using triangulation technology and would facilitate triggering localised alarms or group decisions for several assets. Moreover, readers will no longer be useful, as already discussed.

8 Conclusion

CPS-based maintenance has the potential to be valuable for any airline seeking to improve the quality and effectiveness of a range of replacement tasks. This will in turn reduce the costs associated with maintaining aircraft assets that exist in a large number of identical replaceable elements.

This paper presented a study aimed at estimating the feasibility conditions for implementing a CPS that achieves a balanced maintenance policy for aircraft assets in the near future. The paper presents the first step in analyzing the financial conditions that will enable a company to beneficially adopt a CPS-based approach to dynamically balance preventive and corrective maintenance.

Applied to seat covers in this particular study, our approach is nevertheless designed in a generic way to be applied easily to other aircraft assets, and the findings in this paper form the basis for further research. From these results, it is possible for aircraft asset management companies to evaluate the risk of implementing a full CPS system for balanced preventive and corrective asset maintenance. The suggested numerical scenario and mathematical models can be improved to gain accuracy and precision. Moreover, a future extension of the suggested CPS would enable assets to self-schedule cooperatively and in real time, allowing replacement tasks to be integrated into smaller packages that require fewer person-hours; therefore, the replacement tasks could be conducted in smaller time windows of aircraft availability.

9 Acknowledgments

Surferlab is partially funded by the European Regional Development Fund (ERDF), and the authors wish to thank the European Union and the Nord–Pas-de-Calais in France for their support. The authors also wish to thank EAM Worldwide for their support.

10 References

[1] Wittmer, A., Bieger, T., Müller, R.: '*Aviation systems: management of the integrated aviation value chain*' (Springer Science & Business Media, Berlin, 2011)

[2] Lampe, M., Strassner, M., Fleisch, E.: 'A ubiquitous computing environment for aircraft maintenance'. Proc. ACM Symp. Applied Computing, Nicosia, March 2004, pp. 1586–1592

[3] Fritzsche, R., Lasch, R.: 'An integrated logistics model of spare parts maintenance planning within the aviation industry', *World Acad. Sci. Eng. Technol.*, 2012, **68**, pp. 1–11

[4] Markou, C., Cros, G.: 'Industry trends maintenance cost'. IATA 3rd Airline Cost Conf., Geneva, August 2015, p. 26

[5] Andreacchio, M., Bekrar, A., Benmansour, R., *et al.*: 'Balancing preventive and corrective maintenance of aircraft assets: a cyber-physical systems approach'. IEEE 14th Int. Conf. on Industrial Informatics, Poitiers, July 2016, pp. 500–503

[6] Price, A.: 'An opportunity analysis for efficient parts management in airlines'. IATA Simplifying the Business, Vancouver, June 2007, pp. 12–17

[7] Williams, C.: 'Analysing the 737NG's first base checks', *Aircraft Commer.*, 2006, (46), pp. 48–52

[8] Williams, C.: '737NG maintenance analysis & budget', *Aircraft Owner's Operator's Guide*, 2010, (45), pp. 18–28

[9] Yan, S., Chen, C.-Y., Yuan, C.-Y.: 'Long-term aircraft maintenance scheduling for an aircraft maintenance centre: a case study', *Int. J. Appl. Manage. Sci.*, 2008, **1**, (2), pp. 143–159

[10] Stenström, C., Norrbin, P., Parida, A., *et al.*: 'Preventive and corrective maintenance–cost comparison and cost–benefit analysis', *Struct. Infrastruct. Eng.*, 2016, **12**, (5), pp. 603–617

[11] Dekker, R., Wildeman, R.E., Schouten, F.A.V.: 'A review of multi-component maintenance models with economic dependence', *Math. Methods Oper. Res.*, 1997, **45**, (3), pp. 411–435

[12] McCall, J.J.: 'Maintenance policies for stochastically failing equipment: a survey', *Manage. Sci.*, 1965, **11**, (5), pp. 493–524

[13] Pierskalla, W.P., Voelker, J.A.: 'A survey of maintenance models: the control and surveillance of deteriorating systems', *Nav. Res. Logist.*, 1976, **23**, (3), pp. 353–388

[14] Zequeira, R., Bérenguer, C.: 'Optimal inspection policies with predictive and preventive maintenance', *Eng. Optim.*, 2005, **37**, (5), pp. 541–550

[15] Charles, A.-S., Floru, I.-R., Azzaro-Pantel, C., *et al.*: 'Optimization of preventive maintenance strategies in a multipurpose batch plant: application to semiconductor manufacturing', *Comput. Chem. Eng.*, 2003, **27**, (4), pp. 449–467

[16] Khalil, J., Saad, S.M., Gindy, N.: 'An integrated cost optimisation maintenance model for industrial equipment', *J. Qual. Mainten. Eng.*, 2009, **15**, (1), pp. 106–118

[17] Wan, J., Tang, S., Li, D., *et al.*: 'A manufacturing big data solution for active preventive maintenance', *IEEE Trans. Ind. Inform.*, 2017, **13**, (4), pp. 2039–2047

[18] Ferrer, G., Apte, A.U.: 'Managing life-cycle information of aircraft components', *Defence ARJ.*, 2012, **19**, pp. 161–180

[19] Saygin, C., Tamma, S.: 'RFID-enabled shared resource management for aerospace maintenance operations: a dynamic resource allocation model', *Int. J. Comput. Integr. Manuf.*, 2012, **25**, (1), pp. 100–111

[20] Algera, D., Iyyer, N., Hong, C., *et al.*: 'Rotary wing structural life tracking architecture'. 66th American Helicopter Society Forum, Phoenix, AZ, May 2010

[21] Gramopadhye, A.K., Drury, C.G.: 'Human factors in aviation maintenance: how we got to where we are', *Int. J. Ind. Ergon.*, 2000, **26**, (2), pp. 125–131

[22] Xu, L.D., He, W., Li, S.: 'Internet of things in industries: a survey', *IEEE Trans. Ind. Inform.*, 2014, **10**, (4), pp. 2233–2243

[23] Lee, E.A.: 'Cyber physical systems: design challenges'. 11th IEEE Int. Symp. Object Component Oriented Real Time Distributed Computing, Orlando, FL, 2008, pp. 363–369

[24] Shu, Z., Wan, J., Zhang, D., *et al.*: 'Cloud-integrated cyber-physical systems for complex industrial applications', *Mob. Netw. Appl.*, 2016, **21**, (5), pp. 865–878

[25] Gong, H., Li, R., An, J., *et al.*: 'Scheduling algorithms of flat semi-dormant multicontrollers for a cyber-physical system', *IEEE Trans. Ind. Inform.*, 2017, **13**, (4), pp. 1665–1680

[26] Rahman, M.S., Mahmud, M.A., Oo, A.M.T., *et al.*: 'Multi-agent approach for enhancing security of protection schemes in cyber-physical energy systems', *IEEE Trans. Ind. Inform.*, 2017, **13**, (2), pp. 436–447

[27] Cardin, O., Ounnar, F., Thomas, A., *et al.*: 'Future industrial systems: best practices of the intelligent manufacturing and services systems (IMS2) French research group', *IEEE Trans. Ind. Inform.*, 2017, **13**, (2), pp. 704–713

[28] Otto, J., Vogel-Heuser, B., Niggemann, O.: 'Automatic parameter estimation for reusable software components of modular and reconfigurable cyber-physical production systems in the domain of discrete manufacturing', *IEEE Trans. Ind. Inform.*, 2017, **14**, (1), pp. 275–282

[29] Jiang, Y., Song, H., Wang, R., *et al.*: 'Data-centered runtime verification of wireless medical cyber-physical system', *IEEE Trans. Ind. Inform.*, 2016, **13**, (4), pp. 1900–1909

[30] Truong, V.N., Joon, L.S., Won, L.C., *et al.*: 'An implementation of laundry management system based on RFID hanger and wireless sensor network'. 4th Int. Conf. Ubiquitous Future Networks, Phuket, 2012, pp. 490–493

[31] Lodgher, A.: 'Managing a laundry using RFID-based automated processes', *Commun. IIMA*, 2009, **9**, (3), p. 71

[32] Lu, Y., Yu, H.: 'A flexible architecture for RFID based laundry management systems'. 6th Int. Conf. Wireless Communications Networking Mobile Computing, Chengdu, September 2010, pp. 1–4

[33] Fu, Y.Y., Chan, Y.L., Yang, M.H., *et al.*: 'Experimental study on the washing durability of electro-textile UHF RFID tags', IEEE *Antennas Wirel. Propag. Lett.*, 2015, **14**, pp. 466–469

[34] Dovere, E., Cavalieri, S., Ierace, S.: 'An assessment model for the implementation of RFID in tool management', *IFAC-PapersOnLine*, 2015, **48**, (3), pp. 1007–1012

[35] Thorne, A., Barrett, D., McFarlane, D.: '*Impact of RFID on aircraft turnaround processes*' (Auto-ID Laboratory, University of Cambridge, Cambridge, UK, 2007)

[36] Andreacchio, M.: 'Reducing aircraft life vest underutilisation by implementing RFID-enabled inspections'. 4th Int. Conf. Advanced Logistics and Transport, Valenciennes, May 2015, pp. 7–11

[37] Harrison, M.: '*Guidelines for lifecycle ID & data management*' (Auto-ID Laboratory, University of Cambridge, Cambridge, UK, 2007)

[38] Ngai, E.W.T., Cheung, B.K.S., Lam, S.S., *et al.*: 'RFID value in aircraft parts supply chains: a case study', *Int. J. Prod. Econ.*, 2014, **147**, pp. 330–339

[39] Karygiannis, T., Eydt, B., Barber, G., *et al.*: 'Guidelines for securing radio frequency identification (RFID) systems', *NIST Spec. Publ.*, 2007, **80**, pp. 1–54

[40] Ngai, E.W.T., Cheng, T.C.E., Lai, K.-H., *et al.*: 'Development of an RFID-based traceability system: experiences and lessons learned from an aircraft engineering company', *Prod. Oper. Manage.*, 2007, **16**, (5), pp. 554–568

[41] Klueber, R., O'Keefe, R.M.: 'Defining and assessing requisite supply chain visibility in regulated industries', *J. Enterp. Infor. Manage.*, 2013, **26**, (3), pp. 295–315

[42] Sampigethaya, K., Poovendran, R., Bushnell, L.: 'Secure operation, control, and maintenance of future E-enabled airplanes', *Proc. IEEE*, 2008, **96**, (12), pp. 1992–2007

[43] Brintrup, A., McFarlane, D., Ranasinghe, D., *et al.*: 'Will intelligent assets take off? Toward self-serving aircraft', *IEEE Intell. Syst.*, 2011, **26**, (3), pp. 66–75

[44] Mertins, K., Knothe, T., Gocev, P.: 'Towards CPS based aircraft MRO', in Camarinha-Matos, L.M., Xu, L., Afsarmanesh, H. (Eds.): '*Collaborative networks in the internet of services*' (Springer, Berlin, 2012), pp. 166–173

[45] Trentesaux, D., Knothe, T., Branger, G., *et al.*: 'Planning and control of maintenance, repair and overhaul operations of a fleet of complex transportation systems: a cyber-physical system approach', in Borangiu, T., Thomas, A., Trentesaux, D. (Eds.): *'Service orientation in holonic and multi-*

agent manufacturing', Studies in Computational Intelligence (Springer International Publishing, Berlin, 2015), pp. 175–186
[46] Zhang, L.: 'Convergence of physical system and cyber system modeling methods for aviation cyber physical control system'. IEEE Int. Conf. Information and Automation, Hailar, July 2014, pp. 542–547
[47] Sampigethaya, K., Poovendran, R.: 'Cyber-physical integration in future aviation information systems'. IEEE/AIAA 31st Digital Avionics Systems Conf., Williamsburg, VA, October 2012, pp. 1–18
[48] Sampigethaya, K., Poovendran, R.: 'Aviation cyber & physical systems: foundations for future aircraft and air transport', *Proc. IEEE*, 2013, **101**, (8), pp. 1834–1855
[49] Sampigethaya, K., Poovendran, R.: 'Cyber-physical system framework for future aircraft and air traffic control'. IEEE Aerospace Conf., Big Sky, MT, March 2012, pp. 1–9
[50] Huebner, A., Facchi, C., Meyer, M.*, et al.*: 'RFID systems from a cyber-physical systems perspective'. Proc. 11th Workshop Intelligent Solutions Embedded Systems, Pilsen, September 2013, pp. 1–6
[51] SAE: 'AS5678A: passive RFID tags intended for aircraft use. G-18 radio frequency identification (RFID) aero applications', 2015
[52] FAA: '*Advisory circular: airworthiness approval and operational allowance of RFID systems*' (U.S. Department of Transportation, Federal Aviation Administration, 2008)
[53] ARINC: '*Standard: ARINC673 guidance for the use of UHF radio frequency identification (RFID)*' (ARINC Industry Activities, 2009)
[54] ATA: '*Spec 2000 chapter 9: automated identification and data capture*' (Air Transport Association, 2009)
[55] Barlow, R., Hunter, L.: 'Optimum preventive maintenance policies', *Oper. Res.*, 1960, **8**, (1), pp. 90–100
[56] Barlow, R.E., Proschan, F.: '*Mathematical theory of reliability*' (Society for Industrial and Applied Mathematics, Philadelphia, PA, 1996)
[57] Savits, T.H.: 'Some multivariate distributions derived from a non-fatal shock model', *J. Appl. Probab.*, 1988, **25**, (2), pp. 383–390
[58] Wang, H., Pham, H.: 'Some maintenance models and availability with imperfect maintenance in production systems', *Ann. Oper. Res.*, 1999, **91**, pp. 305–318
[59] Valdez-Flores, C., Feldman, R.M.: 'A survey of preventive maintenance models for stochastically deteriorating single-unit systems', *Nav. Res. Logist.*, 1989, **36**, (4), pp. 419–446
[60] Bergman, B.: 'On the optimality of stationary replacement strategies', *J. Appl. Prob.*, 1980, **17**, (1), pp. 178–186
[61] Skytrax: 'Cabin cleanliness is a competitive differentiator for airlines'. Available at http://www.airlinequality.com/news/airline-cabin-cleanliness/
[62] Williams, C.: '*Maintenance differences between freighters & passenger aircraft*' (Aircraft Commerce, Horsham, UK, 2015)
[63] FAA: '*Flammability requirements for aircraft seat cushions 25.853-1*' (Federal Aviation Administration, 1986)
[64] IBM: 'IBM ilog CPLEX optimizer, high performance mathematical optimization engines'. Available at http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/