Developing prescriptive maintenance strategies in the aviation industry based on a discrete-event simulation framework for post-prognostics decision making

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A R T I C L E I N F O
Keywords:
- Prescriptive maintenance
- Stakeholder model
- Prognostics and Health Management
- Maintenance decision making
- Discrete-event simulation
- Maintenance strategies
- PreMaDe

A B S T R A C T
The aviation industry is facing an ever-increasing competition to lower its operating cost. Simultaneously, new factors, such as sustainability and customer experience, become more important to differentiate from competitors. As aircraft maintenance contributes about 20% to the overall cost of airline operations and can significantly influence other objectives of an airline as well, maintenance providers are required to constantly lower their cost share and contribute to a more reliable and sustainable aircraft operation. Subsequently, new condition-monitoring technologies have emerged that are expected to improve maintenance operations by reducing cost and increasing the aircraft's availability. As many of these technologies are still in their technological infancy, it is necessary to determine the expected benefit for the airline operations with the given technological maturity and to develop suitable maintenance strategies that incorporate the newly gained insights. With this paper, a discrete-event simulation framework is developed that uses established parameters to describe a condition-monitoring technology's performance and subsequently develops a suitable prescriptive maintenance strategy. Therefore, it enables the adjustment of the optimization goal for the developed strategy to incorporate performance features beyond the frequently used financial indicators. The developed capabilities will be demonstrated for the tire pressure measurement task of an Airbus A320.

1. Introduction
The aviation industry is facing an ever-increasing competition for lower operating costs in order to gain competitive advantages and, subsequently, market shares [1]. With the liberalization of the aviation market and the emergence of low cost carriers, traditional airlines faced the challenge to lower their operating costs in order to remain competitive [2,3]. Additionally, factors influencing the passenger experience, such as flight delays and cancellations, have become an increasingly critical indicator of the carrier’s quality as passengers expect an affordable service that operates reliably on time [4]. As a result, air transport operators seek to minimize their cost while achieving high standards of safety and service, i.e. improving their operability [5]. As aircraft maintenance contributes between 7% and 17% to an airline’s Direct Operating Cost (DOC) [6–8] and can additionally cause significant operational irregularities [9,10], Maintenance, Repair, and Overhaul (MRO) providers are increasingly required to reduce their respective DOC share.

Additionally, the ecological impact of aviation is continuously gaining in importance due to the increasing environmental awareness of customers, society, and politics [11]. In 2016, the aviation sector was accountable for about 3.6% of the total anthropogenic Greenhouse Gas (GHG) emissions. This share, however, is expected to increase due to the projected steady growth of air traffic [12]. Consequently, higher sustainability requirements for all involved aviation stakeholders, including MRO providers, can be expected. Although the true environmental impact of maintenance has not been exhaustively examined in previous studies yet, Airbus, in conjunction with the European Commission, indicates its contribution’s significance [13].

Subsequently, aircraft operators and MRO providers have started to employ new, emerging digital technologies to detect faults at an early stage and project upcoming failures before they occur. Thus, these approaches are expected to have a significant positive impact on the overall maintenance operations and sustainability. Groenenboom [14] estimates the worldwide savings potential by employing digitalization technologies to improve maintenance operations and adjacent logistics processes to be about $3 bn. per year. Driven by this potential, multiple efforts in research and industry have been undertaken to develop a...
the effects of different technological maturity levels of PHM systems. It showed that there is hardly any work existing specifically examining different maturity parameters to reflect on differences in diagnosing under laboratory conditions. Therefore, it is necessary to incorporate the majority of these PHM systems are still at lower levels of necessary spare part stock level. Their aim was to optimize the business performance along the supply chain, e.g. the aircraft, itself rather than incorporating adjacent processes through a variation of the underlying Prognostic Horizon (PH). However, both of these studies neglected the consideration of varying fleet utilization degrees of PHM systems.

In addition to the limited consideration of different technological maturity levels, existing studies almost exclusively focus solely on cost aspects and neglect other relevant objectives that can be affected. Particularly, adversarial environmental effects of specific maintenance decisions are usually neglected or estimated in an over-simplified approach as economic input–output analysis (ref. Chestnut and Howarth [21], Sobret et al. [22], Dallara et al. [23]). Albeit not being within the research area of aviation maintenance, Nakousi et al. [24] presented a maintenance scheduling approach that allows the simultaneous optimization of maintenance costs and GHG emissions for a mining truck fleet. They also considered aspects of the imperfectness of restorative maintenance actions in order to derive an optimized maintenance plan that minimizes the maintenance costs while maintaining or even increasing the individual truck’s production rate. However, their paper also lacks the consideration of different stakeholders and varying PHM maturity levels.

Finally, the vast majority of existing methods possess an asset-centric view, i.e. they focus in their evaluation analyses on the asset, e.g. the aircraft, itself rather than incorporating adjacent processes within the involved stakeholders. Examples for this asset-centricity are from Aizpurua et al. [25] and Shi et al. [26], respectively. Aizpurua et al. [25] developed a dynamic maintenance scheduler that incorporates prognostics information for critical items and subsequently derives restorative actions. Shi et al. [26] described a similar framework that allows the grouping of preventive maintenance tasks for various systems based on their projected reliability and a given minimum reliability threshold. Both of them focused in their respective publications on the minimization of maintenance cost.

In summary, the following limitations exist in research that need to be addressed:

- Maintenance decision optimization is often done for either preventive maintenance or PHM technologies without consideration of varying technological maturity levels and fleet utilization degrees.
- Most existing work solely focuses on the asset itself and, therefore, allows only a limited consideration of multi-stakeholder scenarios and of the asset’s behavior in its ecosystem.
- Studies strongly utilize monetary factors to measure their framework’s performance with little to no consideration of non-monetary aspects, e.g. adversarial environmental impact.

Thus, the aim of this paper is to develop a prescriptive maintenance decision making algorithm that enables users to assess the economic and ecologic impacts for the key stakeholders aircraft operators and maintenance provider. This decision making algorithm will be applied for different technological maturity levels of the underlying PHM technology and for varying utilization degrees within a given fleet. Subsequently, we want to allocate the expected impact to the respective stakeholder to identify potential improvements or drawbacks for their individual objectives. Based on our previous work [20], we will utilize the developed discrete-event simulation environment PreMaDe (Prescriptive Maintenance Developer) and extend its functionalities to allow

| Acronyms | Description |
|----------|-------------|
| CBM      | Condition Based Maintenance |
| CND      | Cannot Duplicate |
| DES      | Discrete-Event Simulation |
| DMC      | Direct Maintenance Cost |
| DOC      | Direct Operating Cost |
| EOL      | End of Life |
| GHG      | Greenhouse Gas |
| LCBA     | Lifecycle Cost-Benefit Analysis |
| LRU      | Line Replaceable Unit |
| MLG      | Main Landing Gear |
| MPD      | Maintenance Planning Document |
| MRO      | Maintenance, Repair, and Overhaul |
| MTTF     | Mean Time To Failure |
| MTTR     | Mean Time To Repair |
| NFF      | No Failure Found |
| NLG      | Nose Landing Gear |
| PAX      | Passenger |
| PH       | Prognostic Horizon |
| PHM      | Prognostics and Health Management |
| RCM      | Reliability Centered Maintenance |
| ROI      | Return on Investment |
| RUL      | Remaining Useful Lifetime |
| TAT      | Turnaround Time |
| TPIS     | Tire Pressure Indication System |
| UTC      | Universal Time Coordinated |
the evaluation of the above mentioned scope. Within this paper, these effects shall be demonstrated with the help of a Tire Pressure Indication System (TPIS) for an Airbus A320. The corresponding pressure maintenance task suits the intended analysis since – for the conventional maintenance approach – it occurs frequently, due to its short time intervals, and possesses a comparably limited technological complexity to simulate degradation [20].

Summarizing, with the here presented work, we will extend the existing knowledge in the area of maintenance decision making in the aviation industry by:

• deriving and quantifying optimized maintenance decisions for different stakeholder perspectives with the introduction of PHM technologies.
• examining the effect of different technological maturity levels and utilization degrees within a fleet to derive minimum performance criteria for the developed condition monitoring technology.
• extending the scope of traditional maintenance decision making goals with their predominant orientation towards the maximization of monetary objectives by including non-monetary aspects, e.g. through the consideration of an adversarial environmental impact.

Having presented the scope of this paper, the remainder of this work is structured as follows: After a brief overview of the evolution of legacy aircraft maintenance strategies, we will discuss different proactive maintenance approaches, particularly prescriptive aircraft maintenance, with their individual key features and characteristics. Based on these insights, we will then present the concept and structure of the underlying decision making tool PreMaDe and, finally, estimate the expected implications of the developed prescriptive maintenance approach for the involved stakeholders.

2. Evolution of aircraft maintenance strategies

In order to identify the key features of new maintenance strategies resulting from a continuous condition monitoring, we need to examine the foundations of conventional aircraft maintenance and to define its main objectives and limitations. For the understanding of this section and the rest of this paper, it is necessary to define two fundamental distinctions of maintenance strategies that we use in the following sections. These are:

Corrective maintenance. This maintenance strategy includes all maintenance actions that are issued and completed after a failure occurrence, i.e. reacting on a system failure and rectifying it as a consequence of it.

Proactive maintenance. All forms of maintenance that include regular functionality checks to either identify upcoming faults or project failures prior to their occurrence are defined to be proactive.

2.1. Conventional aircraft maintenance

The basis for aircraft maintenance builds on the approach of Reliability Centered Maintenance (RCM), i.e. a generic decision process to identify preventive measures that are needed to manage and control failure modes which otherwise could result in functional failures [27]. The key assumption of the RCM approach is that the reliability of an item depends on its design and its condition at the time of manufacturing [5]. According to Nowlan and Heap [28], effective maintenance and inspection requirements can be derived for this approach based on the following procedure:

• Examination of key contributors leading to a functional failure,
• Consideration of the expected consequences from an occurring failure, and
• Determination of preventive measures and their consequences for safe and reliable operation.

These aspects will be thoroughly evaluated to determine a cost-effective preventive, i.e. scheduled, maintenance program that can ensure the operational safety [29]. However, it has to be noted that the main target of RCM is not to avoid failures per se, but to mitigate their consequences towards operational safety [30]. Hence, the RCM approach will concentrate on the preservation of a system's functionality rather than focusing on the correct mode of operation for all its hardware components [5].

Once the applicable maintenance tasks have been defined, the necessary intervals for task execution need to be determined. Historically, these intervals have been derived from statistics of past operations (e.g. through the Mean Time To Failure (MTTF)) or are based on engineering experience with comparable systems [31]. However, as Rausand [32] emphasizes, especially for new systems, there is often a lack of knowledge about the degradation behavior and failure mechanisms. Hence, in order to ensure a safe operation, applicable maintenance intervals will often be estimated conservatively, resulting in shorter maintenance intervals than actually necessary. Additionally, they will be closely monitored until sufficient information about the system degradation has been obtained, leading to an excess of (unnecessary) maintenance activities. [31,32]

Although the development of scheduled maintenance tasks has become increasingly sophisticated, a large portion of aircraft maintenance activities results from unscheduled maintenance. These are tasks that have not been accounted for in the regular planning procedure and are primarily issued due to detected system abnormalities. By definition, unscheduled maintenance is non-routine maintenance; thus, these terms are often used synonymously [33,34]. Although unscheduled maintenance is most often associated with a chosen corrective maintenance approach, there is also the possibility to have unscheduled maintenance as a consequence of previously conducted scheduled maintenance task, e.g. removing a failed component that has been identified through routine testing [27,34,35].

As Ackert [36] points out, the amount of non-routine maintenance tasks regularly exceeds the number of routine maintenance tasks for matured system conditions after the first heavy base maintenance event. Similar results have been stated by Kählert [8] and Heisey [33] in their work. While Kählert [8] determines that unscheduled maintenance accounts for 88% of an airline’s Direct Maintenance Cost (DMC), Heisey [33] emphasizes that non-routine labor and material cost are the primary causes of increasing maintenance cost. Subsequently, operators and manufacturers strive to reduce non-routine maintenance because of its effect on schedule reliability and airplane downtime [33].

2.2. Condition-based aircraft maintenance

To overcome the limitations of the current scheduled maintenance approach, aircraft maintenance providers are shifting their focus from a time-based maintenance schedule towards a condition-based maintenance logic. As stated before, the main goal for RCM is to assure a system’s functionality and not necessarily to provide a continuous insight into the system’s state of degradation. This approach leads to unnecessary maintenance tasks and its elimination offers a significant savings potential for the maintenance task execution itself as well as for surrounding processes [17]. Subsequently, many condition-monitoring technologies have been developed over the course of the years, e.g. for hydraulic systems [37,38], aircraft engines [39-41], and airframe structures [42,43]. All these developed methods’ key objective is to enable a constant insight into a system’s state of degradation and, ultimately, project failure events before their occurrence. [44,45]

In addition to this, multiple strategies have been derived to allow an exploitation of the generated insights (ref. Fig. 1) [46]. In general, two main groups of proactive maintenance measures can be distinguished: diagnostic and prognostic maintenance. Diagnostic maintenance is characterized by its capability to detect and isolate upcoming faults
within a system or component at an early stage due to abnormal sensor readings or system behavior [47]. Extending this insight into the current state of degradation by future utilization and projecting the degradation propagation until the point of failure will subsequently enable prognostic maintenance [47]. As of this paper, we will not discuss all different proactive maintenance strategies in detail, but briefly describe them and primarily focus on the most recent development of prescriptive maintenance strategies. For additional information, interested readers are kindly referred to Ansari et al. [48], Nemeth et al. [49], and Soltanpoor and Sellis [50].

The evolution of the individual strategies with their respective major objectives can be seen in Fig. 2. As the figure illustrates, the generated benefit has increased and is still expected to increase continuously with every extension of the maintenance strategy's scope. However, that benefit comes at the cost of a steadily increased level of complexity. In general, four major development steps can be identified (although some papers may argue that there are additional steps, e.g. in [54]). These are:

- **Descriptive Maintenance**: The most fundamental form of proactive maintenance that is based on records of historical maintenance data and observed failure events to identify what observed equipment failure has resulted in which specific maintenance measure. [48,55]

- **Diagnostic Maintenance**: This approach additionally considers information about operating and system conditions to develop cause-effect-relationships and to allow the clear identification of root causes leading to the ultimate system failure. [48,49]

- **Predictive Maintenance**: As arguably the most discussed maintenance strategy in recent years, the focus here is on extending the knowledge about degradation mechanisms and extending the degradation propagation into the future to project system failures. Subsequently, this approach utilizes the knowledge discovery process and combines insights into the experienced degradation in the past with anticipated operating loads in the future in order to support a maintenance decision making process. [49,50,55]

- **Prescriptive Maintenance**: This approach will utilize the information about degradation projections and extend the scope of the maintenance decision making process beyond the asset itself, e.g. the aircraft. Thus, by consideration of the surrounding ecosystem, a prescriptive maintenance strategy will allow a holistic analysis and optimization of maintenance measures. [48]

Conventional – and even established proactive maintenance approaches – possess a strong asset-centricity, i.e. the knowledge about a system’s Remaining Useful Lifetime (RUL) provides only an indication about their respective condition and does not consider any limitations in adjacent processes [56]. Thus, information about the system’s degradation status does not necessarily guarantee the generation of any benefit for the involved stakeholders. Prescriptive maintenance strategies will, therefore, extend the scope of the maintenance decision making process to proactively schedule necessary maintenance related downtimes in order to avoid system failures while minimizing any adversarial effects on the involved stakeholders. Ultimately, this approach will utilize the knowledge about the projected equipment failure together with information such as

- necessary ground resources and their availability,
- needed spare parts and their required logistic lead times, and
- the minimum downtime for the maintenance task completion

to evaluate possible maintenance opportunities towards their expected implication on the involved stakeholder’s objectives. Subsequently, this approach will select the maintenance opportunity for task execution that allows the optimization of the chosen target function, e.g. the minimization of the total maintenance related cost. [48,50,55,57]

3. Proactive maintenance approaches

A key aspect in the development of proactive maintenance approaches is the generation of a continuous insight into an asset’s state of degradation through PHM technologies. As Vachtsevanos and Goebel [58] and Saxena et al. [59] recommend the definition of minimum performance criteria for the efficient development of PHM technologies, we will need to identify relevant indicators to describe these technological capabilities. These will serve as input factors for our simulation to parametrically describe the maturity level of the underlying condition-monitoring technology. Additionally, in order to enable a complete evaluation of the expected impact of such a technology for the involved stakeholders, we need to consider their respective objectives. The corresponding evaluation metrics will be addressed by the results of our simulation environment.

3.1. Evaluating the technological maturity of PHM systems

The definition of suitable performance measurement metrics for PHM systems has been the focal point for multiple work, e.g. in Leao et al. [17], Mikat [60], Saxena et al. [61], and Wheeler et al. [62]. Based on these approaches, we will introduce typical evaluation metrics and briefly describe their respective scope. In general, we need to distinguish between metrics for diagnostics and prognostics systems, respectively. On one side, diagnosis metrics focus solely on the monitoring system’s capability to reliably detect upcoming faults in an early stage of their development. On the other side, prognosis metrics aim towards the evaluation of the timeliness and precision of the resulting failure projection.

For the field of diagnostics performance evaluation, one of the most comprehensive works is from Kurtoglu et al. [63]. They introduce the following distinction for the individual performance measurements:

- Detection metrics measure the monitoring system’s ability to correctly indicate a malfunction, e.g. in terms of the fault detection rate or the false positive rate for detection.
- Isolation metrics focus on the correct determination of the fault mode and fault location, e.g. time to isolate or the isolation classification rate.
- Temporal metrics allow an indication of the timeliness of a diagnostics system to respond to an existing malfunction.
- Static metrics evaluate the overall correctness of the fault detection and isolation.

As these performance measurements are expressed in terms of probabilities, the corresponding diagnostics system will need to be subject to an extensive testing routine prior to its utilization. [63]

For the category of prognostics metrics, Saxena et al. [61] and Saxena and Roemer [64] provide a good overview of different existing approaches. They emphasize the distinction between online (also referred to as in-situ) and offline performance metrics. Offline performance metrics will compare the characteristics of the failure prediction with the system’s true End of Life (EOL). These, these metrics require knowledge about the system’s historical failure data and, therefore, only allow a retrospective analysis. These metrics will subsequently allow an evaluation of the prognostic quality, e.g. in terms of the timeliness of the projection or the false alarm rate of the forecast. In order to
enable such an analysis and evaluation of the equipment’s degradation projection throughout its whole lifetime, the underlying systems must have been subject to run-to-failure conditions. Although this category of metrics has been more thoroughly investigated, for many real-world applications this failure data does not exist due to practicality issues or safety concerns. As a result, online performance metrics have been developed. These measurements have the objective to evaluate the observed, true degradation with respect to the projected deterioration for each individual time instance. As a consequence, these metrics do not require any prior knowledge about the true EOL and can be applied throughout the whole process of degradation even before the occurrence of a failure. [64–67]

At this point we will not further discuss each existing metric, but focus on a few general observations with regard to the evaluation of a PHM system’s technological maturity:

- For the support of the maintenance decision making process during live aircraft operation, online performance evaluation metrics for the current system status are predominantly important.
- In order to provide a comprehensive picture of such a technology’s capability, it is not sufficient to focus on individual parameters for the description of the respective technology’s performance. Thus, a thorough evaluation will require the provision of – at least a selection of – the above mentioned performance parameters.
- The economical and ecological evaluation, however, mainly relies on offline evaluation metrics, representing statistical averages for this type of diagnostics and prognostics technology.

3.2. Benefits of proactive maintenance approaches

The determination of possible improvements with the introduction of PHM technologies for various aspects of an airline’s ecosystem has been subject of multiple research work already, e.g. in Kählert [8], Hölz et al. [9], Leao et al. [17], Lee and Mitici [19], Aizpurua et al. [25], Hess et al. [51], Ashby and Byer [68], Hess et al. [69], Rodríguez et al. [70], Sandborn and Wilkinson [71], Sprong et al. [72], Starr [73], and Wheeler et al. [62]. As a general observation, the identified improvements can be clustered into three different groups: operator-related, MRO-related, and logistics-related [62]. Although these clusters allow the general attribution of expected implications to an individual stakeholder, this association may not be exclusive, i.e. the expected benefit may be attributable to multiple involved stakeholders. For example, the reduction of technically-induced flight delays is primarily beneficial for the operator, but can also be an expression of the increased effectiveness of maintenance measures by the MRO provider. The individual objectives and corresponding metrics can vary for each stakeholder (as shown in Table 1) and can effectively lead to different prescriptive maintenance strategies, depending on the goal of the generated maintenance schedule.

For the operator, the overall objective is the assurance of a reliable aircraft operation to achieve a high asset availability for revenue generation [17, 51, 68, 74]. According to Wheeler et al. [62], this objective can be subdivided into the following targets: minimization of necessary Turnaround Times (TATs), minimization or complete avoidance of flight delays or cancellations, and optimal exploitation of the aircraft systems’ MTTF. Besides that, the U.S. Department of Defense [44] emphasizes the capability to perform and complete an assigned mission as a critical factor for aircraft operations. Although this has been stated primarily from a military perspective, this parameter can be translated as the number of unplanned, technically-induced diversions for civilian operations.

The primary objective for an MRO provider is the reduction of maintenance cost. In order to achieve this objective, the following targets can be derived [17, 68, 69, 74]:

- avoidance of No Failure Found (NFF) or Cannot Duplicate (CND) events, i.e. events where a reported in-flight failure cannot be repeated on the ground in order to allow an isolation of the failure,
- reduction of shop visit cost, e.g. through a reduction of material scrap, and
- efficient utilization of available maintenance resources, e.g. through a reliable forecast of maintenance needs and avoidance of unscheduled tasks.

The reduction or complete avoidance of NFF events will not only improve the maintenance process itself as it reduces the occupational time for the necessary ground resources, but will also have implications on the logistics system as it reduces the amount of necessary spare parts inventory. Additionally, MRO providers thrive to reduce the average maintenance downtime for the aircraft by reducing the time needed
for fault identification and isolation as well as the subsequent Mean Time To Repair (MTTR) \cite{17,62,68,72,73}. As stated before, a reduction in maintenance downtimes will automatically improve the aircraft’s availability which is a key target for the operator. Besides these targets for the line maintenance, MRO providers also aim for a reduction of the necessary shop maintenance cost following a Line Replaceable Unit (LRU) removal by avoiding unnecessary replacements or costly third party repairs \cite{68,72,73}. Finally, the introduction of diagnostic and prognostic capabilities to allow an early fault detection, for limiting the subsequent damage propagation, will enable MRO organizations to reduce hard-time scheduled functionality check tasks while also predict and schedule necessary restoration measures in advance \cite{17,62,68}.

4. Prescriptive maintenance simulation framework

After we have discussed the theoretical foundations of aircraft maintenance strategy development and presented possibilities to evaluate proactive maintenance approaches, we focus in this section on the presentation of the underlying simulation concept for post-prognostics decision making. The prescriptive maintenance development and simulation framework PreMaDe of DLR’s Institute of Maintenance, Repair and Overhaul is programmed with the logic of a Discrete-Event Simulation (DES). By changing the simulations variables only at times when an event occurs and storing all occurred changes in an object-specific event calendar, a DES is suitable to detect, flexibly adapt to, and analyze different behaviors of the underlying system \cite{75,76}. PreMaDe is programmed in Python to benefit from its open source character and avoid limitations of commercially available products.

4.1. Theoretical foundations of the simulation tool

PreMaDe is based on the idea of the functional relationship stakeholder model shown in Fig. 3. Since a key aspect for prescriptive maintenance is its holistic approach with the inclusion of all key participants in the decision making process, we have defined the following stakeholder as entities in our simulation routine (in accordance with Wheeler et al. \cite{62}):

- the **operator**, who is responsible to conduct flights while checking for curfew restrictions,
- the **maintenance provider**, subdivided into the divisions of line- and shop maintenance, who is responsible to comply with regulatory requirements for a continuing airworthiness and the restoration of the aircraft’s condition, and
- the **logistics provider**, who ensures the timely supply of repair material and manages the necessary inventory of spare parts.

In order to base the derived maintenance decisions on the prediction of individual component failures, it is necessary to additionally include information about (anticipated) system degradations. Although not a stakeholder entity per se, the corresponding **system degradation module** will subsequently allow the calculation of each incremental health deterioration for every individual flight segment with the assumed ambient conditions. All the shown stakeholders are represented through a designated object entity within the simulation environment. PreMaDe is further intended to be built in a modular way and combines all these individual object entities through defined input-/output-interfaces to allow a certain flexibility for future developments.

To limit the scope of this paper, we solely focus on the interaction between the operator and line maintenance to describe their functional dependencies and demonstrate these in our use case scenario. An exemplary extract for this interaction in the specific simulation routine can be seen in Fig. 4. In accordance with the object-orientation, all related entities obtain preprocessed inputs for a faster simulation time. Additionally, the parameters are saved as attributes at the time of the object’s initialization. The program will execute the shown routine from left to right and top to bottom with the following essential steps.

### 4.1.1. User specifications read-in

The various allowable settings (as presented in Section 5.1) will be read in together with necessary database inputs, e.g. the airport database with all information about an airport’s timezone and curfew restrictions. These information will be stored within a designated object and serve as central reference point for key settings throughout the whole subsequent simulation run. It has to be noted that the underlying flight routes, used for the subsequent simulation run, will only contain flight and turnaround times. Thus, the simulation routine will create the corresponding flight schedule by itself (ref. Section 4.1.3).

### 4.1.2. Aircraft fleet and systems initialization

Aircraft and their respective components are the essential object entities that are iterated among the involved stakeholders within the simulation loop and whose attributes are changed to reflect a continuous degradation and aging. They feature individual event calendars to document all flight operations and maintenance tasks that have been conducted with or on the respective aircraft. They further have their individual clock times to track their progression in the simulation run and to identify interactions with the other involved stakeholder, e.g. the time of the execution of maintenance slots. To incorporate different time zones and ensure the correct comparison, all clock times are converted into the Universal Time Coordinated (UTC) format. All aircraft and related systems are assumed to be new at the time of their initialization, i.e. they have not experienced any degradation and their maintenance intervals are set to start with the simulation starting date.

### 4.1.3. Operator module initialization

The operator is responsible to ensure the correct assignment of flights segments to the individual aircraft within the fleet. In order to avoid violations of curfew restrictions, the flight operator object will be supplied with necessary information about non-operating hours within the underlying flight network. At the time of the operator’s initialization, all aircraft will be supplied with an ideal, theoretical flight schedule, according to the user specifications for the intended flight routes. This schedule represents the maximum number of feasible flights for the given flight rotation and applicable curfew restrictions, without any downtimes for maintenance or possible operational irregularities.

| Stakeholder       | Objective                        | Metric                      |
|-------------------|----------------------------------|-----------------------------|
| Operator          | Reduce number of flight delays   | No. of flight delays        |
|                   | Reduce number of flight cancellations | No. of flight cancellations |
|                   | Increase availability            | Aircraft utilization        |
|                   | Increase reliability             | Avg. turnaround time        |
| MRO provider      | Reduce maintenance events        | No. of maintenance events   |
|                   | Avoid component removals         | No. of component replacements|
|                   | Reduce time for troubleshooting   | Avg. maintenance downtime   |
|                   | Maintenance cost reduction       | Avg. maintenance cost per aircraft |
|                   | Improved sustainability          | Avg. maintenance related emissions per aircraft |
4.1.4. Line maintenance provider initialization

An essential part of the line maintenance object is the creation of maintenance stations. These stations are equipped with a certain resource capacity for manual maintenance task execution that can be assigned to specific aircraft when available and needed. These stations also feature their individual event calendars and have their clock times. Additionally, the maintenance provider will ensure the continuing airworthiness for the fleet by monitoring the required functional check intervals, projecting restoration needs, and restoring system conditions.

4.1.5. Initialization of maintenance resources

For this study, we solely focus on necessary mechanics as the required maintenance resources and do not consider any additional ground support equipment. Although these maintenance resources are part of the line maintenance stations, they are created independently since they have individual characteristics (e.g., age, experience level, qualifications). These become particularly important when considering different kinds of maintenance tasks that require specific training or including aspects of imperfect maintenance. The created objects will possess a specific shift duration and are responsible for the execution of the maintenance task. Subsequently, they also feature individual event calendars to track their tasks.

4.1.6. Execution of simulation routine

After all entities have been initialized and necessary information has been assigned to the respective object, the simulation run will be started. The execution of the simulation routine features the following specific steps.

Selection of aircraft. With progression of the simulation, the individual timestamps of the involved object entities will advance differently depending on the duration of their previous event, e.g., a flight segment or a maintenance downtime. Thus, as a first step, the aircraft object with the least progression of its individual clock time will be selected for the next simulation iteration. If there are multiple aircraft with the same clock time they will be chosen according to their alphabetical order of their registration.

Execution of next flight segment. The selected aircraft will first perform the next flight according to its flight schedule. The respective flight segment with essential information such as the take-off, landing, and turnaround time will be stored as an event in the aircraft’s event calendar. With the completion of the flight, the aircraft’s degradation status will be adjusted according to the precalculated health consumption for this flight segment. Other essential aircraft parameters, such as its age, will be updated similarly. In case of an operational irregularity that has lead to the cancellation of the following flight segment, these attributes will not need to be updated. Thus, only the corresponding flight event will be marked as cancellation and stored in the event calendar for later analysis, e.g., the aircraft utilization. Finally, the individual clock time for the aircraft will be forwarded to the ending time of the respective flight event.

Checking for necessary maintenance and resource availability. After the aircraft’s arrival and its experienced progression in system deterioration and age, it needs to be checked whether or not a maintenance task is due to be performed. A maintenance event can be issued by one or multiple of the following triggers:

- The time since the last completion of a scheduled functionality check exceeds the applicable time interval according to the aircraft’s Maintenance Planning Document (MPD) (expressed in terms of flight cycles, flight hours, or calendar days).
- The degraded system condition after completion of the flight is outside of the acceptable limits defined by the manufacturer.
- Based on the predicted system condition and the expected implications on the involved stakeholders (ref. Section 4.2), the aircraft is scheduled to complete a restoration maintenance task.

In order to avoid the issuance of any of these triggers at an airport that is not part of the maintenance base network, all these criteria will also be projected to the next expected time of arrival at a designated line maintenance station. If any of these criteria apply, the respective maintenance provider entity will further check the availability of necessary mechanics. The earliest possible starting time for the maintenance task will be the aircraft’s arrival time plus any applicable cool-down times for the respective system after landing. If an unoccupied resource is available, it will be assigned to execute the maintenance task on the aircraft. Otherwise, the aircraft object’s timestamp will be forwarded until the necessary maintenance task can be completed. After completion of the task, the maintained system’s condition will be restored to its equivalent new condition, neglecting any imperfections of the maintenance. All the corresponding events, i.e., system cool-down time and maintenance task execution, will be stored in the event calendars of the aircraft and chosen mechanic, respectively. Additionally, any occurring waiting times for service will be stored in the aircraft’s event calendar.

Fig. 3. Functional stakeholder model for aircraft maintenance.
Fig. 4. Process simulation routine of the tool PreMaDe.

With the completion of the maintenance tasks, the initially created flight schedule will need to be adjusted accordingly. Thus, for all successive flight segments, the intended take-off and landing times will have to be adapted to incorporate the occurred maintenance downtime. As this downtime is required to retain the aircraft’s airworthiness, these adjustments will not lead to any operational irregularity cost.

Scheduling of next maintenance downtime. This step only applies if the respective aircraft is capable to project upcoming failures and, therefore, allows the proactive scheduling of maintenance requirements. Given the individual system’s prognostic horizon, it first needs to be checked whether or not any upcoming failures can already be reliably predicted. If so, the underlying prescriptive maintenance algorithm (ref. Section 4.2) will calculate the expected implications for the involved stakeholders. This calculation will be done for all successive maintenance opportunities until the time of failure in order to choose the maintenance base visit that optimizes the chosen objective, e.g. the minimization of the total cost or the maximization of the ground resource utilization.

Termination criterion for simulation. After completion of all necessary maintenance tasks and progression of the aircraft specific timestamp, the next aircraft will be selected and iterated accordingly. The simulation is completed once all aircraft timestamps have progressed by the required simulation time span.

4.1.7. Retrieval and analysis of event logs

After the simulation has been completed, the generated event calendars will be retrieved and analyzed. By varying the input parameter to reflect different maintenance approaches and various technological maturity levels, the expected benefits for the involved stakeholders can be calculated based on the entries in these event calendars.

4.2. Prescriptive maintenance planning

After the presentation of the theoretical design of the simulation framework, this section deals with the essential aspects of a prescriptive maintenance strategy.

The basic principle for the identification of maintenance downtimes that allow an optimization of the chosen objective function is depicted in Fig. 5. It consists of the analysis of individual maintenance opportunities, starting with the time of the earliest prediction until the ultimate system’s failure occurrence. A maintenance opportunity is defined as an aircraft’s layover at one of its designated maintenance bases. The execution of a maintenance task at one of these visits will lead to certain implications for every involved stakeholder, i.e. the operator, the line and shop maintenance provider, and the logistics supplier. Thus, for every opportunity, the implications for a chosen objective function will need to be calculated in order to subsequently select the layover that allows an optimization of this function.

Fig. 6 shows a comparison of different maintenance decision outcomes for various underlying strategies: corrective, diagnostic, predictive, and prescriptive maintenance (ref. Section 2). The corresponding time for maintenance task execution – as a result of each maintenance strategy – is indicated by a rectangle around the respective time instance $t_x$. It has to be noted that the underlying aircraft system, operational load, and subsequent degradation are assumed to be equal.
for each of these depicted cases in Figs. 6(a) and 6(b). Each individual time step \( t_1, \ldots, t_9 \) symbolizes a maintenance opportunity. We assume for the shown scenario that the system will ultimately fail and require a maintenance task at time instance \( t_9 \).

The first subplot (ref. Fig. 6(a)) shows the maintenance decision for a corrective and a diagnostic maintenance approach, respectively. Since a strictly corrective maintenance approach has no functionality checks prior to a failure occurrence, there is no information about any degradation progression available. Subsequently, the restorative maintenance task will be issued at time instance \( t_9 \) with the system’s failure. In contrast, a diagnostic maintenance strategy will incorporate regular functionality checks – in this exemplary scenario at the time instances \( t_1, t_3, t_5, \) and \( t_7 \). Each measured condition will be either automatically or manually compared against a predefined degradation threshold, e.g. given by the manufacturer or regulatory authorities. In order to avoid system failures, this threshold is usually chosen more conservatively with some safety margin incorporated. Once the degradation has exceeded the allowable limit (ref. time instance \( t_9 \)), a corresponding maintenance task will be issued.

By taking the capabilities of failure projections into account (as shown in Fig. 6(b)), we will not only be able to compare the current system degradation against a given threshold, but also forecast future degradation. This projection is indicated by the dashed line on the very left in Fig. 6(b); therefore, at the current time stamp, all maintenance opportunities are still in the future. Additionally, these prognostics-based maintenance approaches will extend the scope beyond the mere consideration of degradation progress by quantifying the expected (monetary) implications. As discussed in Section 2.2, predictive maintenance approaches are characterized by their asset-centricity; thus, the related cost elements can only include those that are directly linked to the system, i.e. task and waste-of-life cost. Subsequently, a predictive maintenance approach will try to balance the growing task costs due to an increased required work scope (close to a failure occurrence) with penalty cost for premature part replacements (which steadily decrease towards the system’s failure). In the shown scenario, these cost aspects are minimal at time instance \( t_9 \). Ultimately, the prescriptive maintenance strategy will additionally consider aspects of adjacent processes and stakeholders, e.g. operational irregularity cost or penalty cost for any maintenance-related emission. In the shown scenario, this consideration leads to shift of the favorable maintenance downtime at time instance \( t_9 \). Albeit being more expensive from a mere asset-centric perspective, the superiority of other factors, e.g. the necessary resource availability or the compliance with higher environmental standards, will lead to a more holistic consideration in the maintenance decision making process.

In a previous study [20], we have developed a prescriptive maintenance strategy that focused exclusively on the reduction of waiting times for occupied ground resources. For this paper, we will extend this scope by including avoidable operational irregularity cost as well as adding adversarial environmental impacts into the decision making process. Thus, the overall objective for the developed prescriptive maintenance strategy is to minimize the total maintenance related cost. For a better understanding of its implementation, the underlying program routine for this paper is also presented in terms of a pseudocode example (ref. alg. 1). The corresponding function for each maintenance opportunity is defined as

\[
\sum_{\text{in } S} c^{\text{maint}}_{t} + c^{\text{waste}}_{t} + c^{\text{rest}}_{t}
\]  

(1)

with maintenance tasks for all subsystems \( S \) of the respective aircraft system \( S \) at aircraft \( k \). According to Eq. (1), the expected total cost are composed of the following cost components:

**Maintenance-related cost.** This includes all costs that can directly be related to the execution of the respective maintenance tasks, e.g. cost for personnel, material cost, etc. Thus, they depend on the necessary work scope and can be calculated through the following equation:

\[
c^{\text{maint}}_{k} = r^{\text{task}}_{t} \cdot c^{\text{labour}} + c^{\text{mat}} + c^{\text{emission}} \cdot c^{\text{task}}
\]  

(2)

with \( r^{\text{task}}_{t} \) as the duration for the task completion, \( c^{\text{labour}} \) as the labor cost for the involved mechanic, \( c^{\text{mat}} \) as the cost for the necessary repair material, \( c^{\text{emission}} \) as the task-related environmental impact, and \( c^{\text{task}} \) as the corresponding penalty factor for emissions.

**Cost of waste-of-life.** These cost are the result of premature maintenance or replacement and the underutilization of the available system lifetime, as discussed by Hölzel [9] and Meissner et al. [20]. This underutilization factor is calculated as follows:

\[
P_{\text{remain}} = \frac{(p^{\text{proj}}_{f} - p^{\text{prod}}_{f})}{(P_{\text{max}} - P_{\text{min}})}
\]  

(3)

where \( p^{\text{proj}}_{f} \) represents the projected system condition after flight segment \( f \), \( p^{\text{prod}}_{f} \) represents the restoration threshold for the simplest form of restorative maintenance, e.g. a tire pressure restoration, and \( P_{\text{max}} \) symbolizes the system’s nominal new condition.

This underutilization factor will subsequently be used to calculate the waste-of-life cost:

\[
c^{\text{waste}}_{t} = \max(0, P_{\text{remain}} \cdot c^{\text{maint}}_{t})
\]  

(4)

It has to be noted though that this value cannot be below zero.

**Operational irregularity cost.** These costs are the result of avoidable extended maintenance downtimes, e.g. through an insufficient availability of necessary mechanics. They strongly depend on the specific time of the day when the delay is occurring, the extent of the delay, and the subsequent flight schedule. In order to minimize their financial loss, airlines may decide to cancel flight segments completely, whenever the anticipated cost of an aircraft delay are higher than the cancellation of flight segments due to delay propagation effects, i.e. subsequent flight schedule changes due to inevitable curfew collisions. Thus, these operational irregularity cost are defined as

\[
c^{\text{delay}}_{f} = \min \left( \sum_{f \in D} c^{\text{delay}}_{f}, \sum_{f \in C} c^{\text{cancel}}_{f} \right)
\]  

(5)

where \( c^{\text{delay}}_{f} \) represents the delay cost for an individual flight segment of all successive delayed flights \( D \) and \( c^{\text{cancel}}_{f} \) represents the alternative cancellation cost for the flight segment of all canceled flights \( C \).
The individual delay cost can be calculated with the following equation:

$$ c^{delay}_{ij} = c^{delay}_{pass} \cdot n^{pass}_{ij} \cdot I^{pass}_{ij} \cdot t^{delay}_{ij} $$

(6)

with $c^{delay}_{pass}$ as the average delay cost per passenger and minute, $n^{pass}_{ij}$ as the maximum seating capacity of the aircraft, $I^{pass}_{ij}$ as the passenger load factor for the respective delayed flight, and $t^{delay}_{ij}$ as the operational delay time. As mentioned before, the occurring delay costs need to be accumulated for all delayed flights $D$ until the delayed aircraft flight schedule caught up with the originally intended one. Similarly, the expected cancellation costs can be calculated through

$$ c^{cancel}_{f} = c^{cancel}_{pass} \cdot n^{pass}_{ij} \cdot I^{pass}_{ij} $$

(7)

where $c^{cancel}_{pass}$ represents the average cancellation compensation for each passenger. It has to be kept in mind that a flight cancellation may not be feasible at any given station, e.g. for remote destinations, as the aircraft may need to be repositioned then, adding additional cost. Additionally, although the individual delay and cancellation compensations may vary depending on the time of their occurrence throughout the day, we simplify the calculation by utilizing an average for these compensation cost.
With all these cost contributions calculated, we can now estimate the total expected cost for each maintenance opportunity and subsequently schedule the maintenance task at an opportunity with minimal resulting maintenance related cost. It has to be noted that the number of maintenance opportunities under consideration significantly depends on the prognostic horizon of the underlying failure projection and the distribution of available maintenance bases within the given flight network.

5. Use case scenario

With all the theoretical foundations set, we will demonstrate the working principle of PsiMaDx with the help of a use case scenario. For this use case we have chosen the tire pressure measurement task of an Airbus A320, as it significantly contributes to the overall scheduled maintenance expenditures [20]. Albeit its comparably short maintenance task times for the execution of functional checks and pressure restoration tasks, the high frequency of required manual functionality checks results in a significant potential for maintenance related cost savings. As of this paper, we will examine different levels of technological maturity for the underlying tire pressure monitoring system and vary its utilization degree, i.e. the ratio of aircraft within the fleet that continuously monitor the tire pressure and are following the prescriptive maintenance approach.

5.1. Simulation input parameter

The first step for this simulation requires the definition of general characteristics for the underlying fleet (ref. Table 2). This includes the definition of the simulation time span, the aircraft type, the fleet size, and compensation payments in the event of an operational irregularity. For this paper, we ran the simulation for a time span of 30 calendar days and examined an exemplary fleet of five Airbus A320 with a seating capacity of 180 Passenger (PAX), operating on short- and medium-haul flights. The passenger load factor has been chosen randomly within a range of 64% and 95% for the underlying flight network. As the necessary turnaround time between each flight can significantly vary, we randomly generated these TATs with a lower limit of 45 min and an upper limit of two hours. Each of the respective aircraft has its main operations hub at Munich airport (MUC). All manual maintenance work, e.g. manual functional checks and pressure restorations, can only be conducted at this airport which serves as the only maintenance base within the chosen flight network.

With these general parameters set, we need to define key maintenance parameters for the tire pressure management task. An overview of related inputs is provided in Table 3. For the system specific parameters, a distinction between the sub-systems Nose Landing Gear (NLG) and Main Landing Gear (MLG) is necessary. All tires are assumed to be manufactured by Goodyear which provides the required maintenance threshold and the lower acceptable pressure limit for the respective task [77]. For example, an NLG tire with a pressure read of 169 psi will require a detailed inspection for any damages together with a resurfuration. In order to allow a certain flexibility for operators, Goodyear has incorporated a safety margin for allowable degradation between the tire's nominal new condition and a lower acceptable pressure limit. If a tire surpasses the maintenance threshold for a detailed inspection (161 psi or 154 psi, respectively), the tire will need to be replaced. As NLG and MLG tires vary in their dimensions, we assumed the associated cost to differ as well, in accordance with Lufthansa Technik [78]. Similarly to these cost assumptions, we have calculated various CO₂ emissions for the individual tasks (see lower part of Table 3). These estimates incorporate the following aspects:

- the average travel distance for the mechanic to get to the aircraft,
- the power consumption for the storage of necessary ground equipment and repair material, and
- the emissions resulting from the production of replacement tires.

To incorporate these CO₂ emissions into the cost calculation, we assume a necessary payment for every ton of emission, e.g. through a taxation as discussed in Osterkamp [79].

As of this paper, we will refrain from describing the conventional tire pressure management approach in more detail. Interested readers are kindly referred to Meissner et al. [80].

In order to determine the necessary downtime for the maintenance task execution, we have used the process time information shown in Table 4. As Goodyear [77] states, the correct measurement of the tire's pressure requires the completion of a cool-down time of 180 min after the last landing. This waiting time is necessary to avoid temperature induced pressure changes. It has to be noted that these cool-down times will not occupy any mechanic resource but only lead to an extended downtime for the aircraft. The subsequent maintenance task times have been retrieved based on information provided by Airbus [81]. Similarly to the maintenance task cost, we have distinguished the task times for the NLG and MLG tires, respectively.

Besides these parameter inputs, we have made the following assumptions for this simulation:

A₁ Maintenance events, i.e. functional checks and restoration tasks, can occur any time throughout the day, but only at designated maintenance hubs.
A₂ Traveling times for the mechanic at the maintenance base have been neglected.
A₃ A mechanic can only serve one aircraft at a time and will only be responsible for the tire pressure restoration task; thus, the resource will be available when no tire maintenance task within the fleet is due.
A₄ As sub-system, e.g. NLG and MLG, can degrade differently, the resulting maintenance tasks will be conducted on a sub-systems level.
A₅ A restoration maintenance task will reset the component to a condition 'as good as new'.
A₆ Ground support equipment, e.g. a trite jack, will always be available when needed and does not experience degradation; therefore, it does not need to be restored.

5.2. Simulation results

With these simulation inputs, we will now examine the implications on maintenance and operations for different maintenance strategies and technological maturity levels of the underlying condition monitoring technology. The conventional tire pressure maintenance approach will serve as our baseline scenario. Starting from there, we subsequently examine the following:

- First, we will analyze the effects for the operator and MRO provider with an automated tire pressure monitoring. Thus, the functional check interval will remain unchanged and only the manual tire pressure measurement will be suspended.
- Second, we will incorporate a prescriptive maintenance approach that is based on the correct and timely prediction of remaining useful lifetimes. In a previous study, we have identified a prognostic horizon of six flight cycles as the necessary lower performance threshold for such a failure projection [20]. Thus, we use this prognostic horizon as the time span for the underlying condition monitoring system and vary the utilization degree for a prescriptive maintenance approach within the fleet.
As first parameter, we want to analyze how the total maintenance related cost change with an increasing utilization degree of an automated condition monitoring and failure projection with the fleet. The utilization degree is defined as ratio of proactively maintained aircraft and the total fleet size. Thus, a ratio of 50% represents an equal split within the fleet of aircraft maintained proactively through a continuous condition monitoring and aircraft that are maintained conventionally with hard-time, interval-based functional checks. The calculated total maintenance related cost include the maintenance task cost itself as well as any cost from resulting operational irregularities, i.e. flight delays or cancellations. The development of these cost is shown in Fig. 7. As can be seen from the graph, the total cost continuously decrease with an increasing technology utilization within the fleet. However, with at least 40% of aircraft within the fleet capable of projecting upcoming maintenance needs at least six flight cycles in advance, the total cost savings seem to hit a plateau with only minor improvements of further introduction of the prognostics technology.

This observation can be supported by considering the individual composition of these total cost for the different scenarios. Fig. 8 shows the absolute values for the maintenance task execution and the resulting operational irregularity cost, respectively. Evidently, by comparing the scales of these two shares, cost resulting from operational irregularities significantly outweigh the mere maintenance task cost. With an increased introduction of prescriptive maintenance approaches within the fleet, these delay and cancellation cost drop from $120,000 for the conventional approach with a manual tire pressure measurement to

### Table 2
Operational parameter.

| Description                  | Parameter | Value | Unit |
|------------------------------|-----------|-------|------|
| Simulation begin             | $t_{\text{start}}$ | 01/01/2020 | –    |
| Simulation time span         | $t_{\text{sim}}$ | 30 days |       |
| Fleet size                   | $n_{\text{ac}}$ | 5     | –    |
| Aircraft type                | $A_{\text{type}}$ | A320 | –    |
| Seating capacity             | $n_{\text{pax}}$ | 180 Pax | –    |
| Passenger load factor        | $I_{\text{pax}}$ | [64, 95] % | |
| Operations hub & maintenance station | $A_{\text{hub}}$ | MUC | –    |
| Turnaround time              | $t_{\text{tat}}$ | [45, 120] min | –    |
| Delay cost per minute and passenger | $c_{\text{delay}}$ | 0.25 $ |       |
| Cancellation cost per passenger | $c_{\text{cancel}}$ | 700 $ |       |

### Table 3
System specific parameter.

| Description                  | Parameter | Value | Value | Unit |
|------------------------------|-----------|-------|-------|------|
| New condition                | $p_{\text{new}}$ | 187 180 psi | $p_{\text{new}}$ | 180 psi |
| Conventional functional check | $I_{\text{conv}}$ | 3 3 days |       |
| Lower acceptable limit       | $p_{\text{acc}}$ | 178 171 psi |       |
| Maintenance threshold restoration | $p_{\text{res}}$ | 170 162 psi |       |
| Maintenance threshold inspection | $p_{\text{insp}}$ | 161 154 psi |       |
| Cost functional check        | $c_{\text{func}}$ | 10 11 $ |       |
| Cost restoration             | $c_{\text{rest}}$ | 50 55 $ |       |
| Cost inspection              | $c_{\text{insp}}$ | 100 110 $ |       |
| Cost replacement             | $c_{\text{rep}}$ | 1000 1100 $ |       |
| Emission functional check    | $e_{\text{func}}$ | 0.061 0.067 kg.CO$_2$ | $e_{\text{func}}$ | 0.067 kg.CO$_2$ |
| Emission restoration         | $e_{\text{rest}}$ | 0.31 0.34 kg.CO$_2$ | $e_{\text{rest}}$ | 0.34 kg.CO$_2$ |
| Emission inspection          | $e_{\text{insp}}$ | 1.23 1.35 kg.CO$_2$ | $e_{\text{insp}}$ | 1.35 kg.CO$_2$ |
| Emission replacement         | $e_{\text{rep}}$ | 3.68 4.04 kg.CO$_2$ | $e_{\text{rep}}$ | 4.04 kg.CO$_2$ |
| Cost emission                | $c_{\text{emis}}$ | 100 100 $ |       |

### Table 4
Process times.

| Description                  | Parameter | Value | Value | Unit |
|------------------------------|-----------|-------|-------|------|
| Cool-down time               | $t_{\text{cool}}$ | 180 180 min |       |
| Time functional check         | $t_{\text{func}}$ | 1 1 min |       |
| Time restoration              | $t_{\text{rest}}$ | 10 12 min |       |
| Time inspection               | $t_{\text{insp}}$ | 45 50 min |       |
| Time replacement              | $t_{\text{rep}}$ | 90 105 min |       |
about $7,000 for a utilization degree of at least 40% and, ultimately, to about $4,000 for a prescriptive maintenance approach of the whole fleet. While the operational irregularity cost eventually reach a plateau, the maintenance task cost can continuously be decreased through an increased introduction of prescriptive maintenance capabilities. This can mainly be attributed to the increasing avoidance of detailed manual inspection tasks due to the increasing continuous condition monitoring and prognosis (ref. Table 5).

With this decrease of total maintenance tasks in general, and detailed inspections in particular, there is an additional saving potential of CO$_2$ emissions. Fig. 9 shows this relative saving potential in terms of cost and emission in relation to the conventional maintenance approach. As can be seen, the mere automation of the functional check task will result in a cost reduction and an equal contribution towards the reduction of adversarial environmental impacts. Like the maintenance task cost, the CO$_2$ emissions also steadily decrease with an increasing utilization of a prescriptive maintenance strategy, reaching a maximum reduction of roughly 30% for the emission and 40% for the task cost, respectively. The spread in saving potential for high degrees of utilization is the result of different weightings for the individual maintenance tasks. Maintenance cost in our simulation are more sensitive towards tasks that are with their scope beyond a simple repressurization. Thus, the complete avoidance of these tasks will subsequently yield a higher proportion of additional saving percentage, compared to the environmental impact.

The examination of individual maintenance tasks with their associated task times is shown in Fig. 10. It shows the distribution of the individual maintenance task times, i.e. system cool-down times, waiting times for occupied resources, and task execution times. All shown values are normalized by the total downtimes for an average aircraft maintained in accordance with the conventional approach.

As we can see, the total downtime decreases continuously up to a prescriptive maintenance fleet utilization of about 40%. Additionally, the plot shows a continuous reduction of waiting times for the necessary ground resources up to a utilization degree of about 80% while the actual task execution times virtually remain unchanged, regardless of the maintenance approach. However, the necessary cool-down times change significantly, not only in their share of the individual bar but also in relation to the benchmark scenario. The reason for this is our chosen prescriptive maintenance approach with the underlying minimization objective. As described in the assumptions (ref. Section 5.1), the individual sub-systems can degrade differently and, therefore, will be maintained independently from one another for the proactive maintenance scenario. Subsequently, the algorithm will allocate each sub-system maintenance task to its preferred maintenance slot in order to avoid unnecessary delays. As the system cool-down time is deemed essential by the manufacturer, its occurrence does not classify as unnecessary. While the conventional maintenance approach has the same functional check interval for both sub-systems, leading to a combined restoration task for all sub-systems, the prescriptive approach will frequently have the sub-systems served individually at different maintenance opportunities. Therefore, the share of cool-down time in the total downtime decreases continuously up to a prescriptive maintenance fleet utilization of about 40%.
times increases with an increased utilization of the proposed prescriptive maintenance approach. Subsequently, reducing the necessary cool-down time before the maintenance task execution will lead to significant savings for the related maintenance downtime.

5.3. Conclusion of this study

In this section we will provide a concluding overview of the presented use case results and briefly discuss limitations of the chosen approach. All the relevant findings for the different maintenance approaches (conventional vs. prescriptive) and utilization degrees are summarized in Table 6 and compared to the conventional maintenance approach which serves as our benchmark. The shown parameters are assigned to the stakeholders MRO provider and operator and should reflect their individual objectives as presented in Table 1. We have selected only two representative utilization degrees to limit the complexity of the table. Thus, we have chosen a utilization degree of 40% and 100%, respectively. As can be seen there, almost all related objectives will continuously improve with an introduction of the proposed prescriptive maintenance approach. The only exception here is the average asset utilization parameter, expressed as the ratio of the maximum number of feasible flights with the given flight schedule and the actual number of completed flights after maintenance execution. This utilization strongly depends on the number of maintenance downtimes and their individual duration. As we have discussed in the previous section, our prescriptive maintenance strategy schedules maintenance tasks on a sub-system level, depending on the sub-system’s respective state of degradation. Thus, although the number of average maintenance tasks per aircraft decreases and the average task execution time remains virtually unchanged, the increase of necessary cool-down times reduces the availability of the respective aircraft. Consequently, as a next step in the improvement of the underlying prescriptive maintenance algorithm, the opportunity cost as the result of a lower aircraft utilization will need to be included in the optimization routine as well.

Based on this study, we can identify the following central findings:

1. F₁ Reducing or completely avoiding necessary times for the system to cool down before executing the maintenance task will help to significantly reduce the resulting maintenance downtimes. Subsequently, this reduction can help to improve the asset utilization.

Additionally, this study has the following limitations that need to be addressed in future work:

1. L₁ In order to derive holistically optimized maintenance schedules, it is necessary to include all essential stakeholders of the airline ecosystem. These include, beyond the operator and line maintenance provider that have been covered here, the logistics provider and shop maintenance facilities.

2. L₂ The maturity of the underlying PHM technology is currently only evaluated through the parameter of the prognostic horizon. As has been discussed in Section 3.1, a variety of applicable performance parameters exist that can be used to describe a diagnostics and prognostics system capability.

6. Summary and outlook

In this paper, we have presented an approach to develop and evaluate prescriptive maintenance strategies based on the technological maturity of an underlying PHM system.

After reviewing conventional aircraft maintenance approaches, we have shown the development of multiple existing proactive maintenance approaches and have discussed their key features. We further have defined prescriptive aircraft maintenance and the necessary aspects that need to be considered in order to derive these holistically optimized maintenance schedules.

As the focus of this study was the support of post-prognostics maintenance decisions and, therefore, strongly relies on the quality and timeliness of failure projections, we have further examined existing approaches to evaluate a PHM technology’s performance to serve as parameter input for our simulation. Additionally, in order to allow a holistic consideration of all involved stakeholders, we have discussed central objectives for the example of aircraft operators and MRO provider. The corresponding evaluation metrics to these objectives serve as performance indicators to determine the resulting quality of the developed maintenance approach within our use case scenario. The relevant stakeholders have been introduced through a stakeholder model that simultaneously builds the foundation of our prescriptive maintenance approach. Subsequently, reducing the necessary cool-down time before the maintenance task execution will lead to significant savings for the related maintenance downtime.

### Table 6

| Strategy | MRO provider | Operator |
|----------|--------------|----------|
|          | C₀₂ emission (in kg.) | Maintenance cost | Detailed inspections | restorations | Number delays | Delay (in hrs.) | Delay cost | Avg. asset utilization |
| Conv. manual | 25.03 | $5,347.60 | 2.0 | 57.2 | 10.6 | 20:00 | $119,729.25 | 91.3% |
| Conv. auto. | 21.17 | $4,488.50 | 2.0 | 57.2 | 10.6 | 20:00 | $117,506.61 | 91.4% |
| Pres. 40% | 19.77 | $4,044.50 | 1.2 | 56.0 | 1.4 | 02:44 | $3,914.28 | 90.4% |
| Pres. 100% | 17.32 | $3,136.50 | 0.0 | 53.2 | 1.0 | 02:06 | $900.54 | 87.4% |
minor expected improvements beyond a minimum utilization degree of 40%. We further analyzed the effects on other key metrics for the considered stakeholders in order to provide an exhaustive evaluation of the developed maintenance strategy for different levels of technological maturities. These showed a possible reduction of maintenance task cost by up to 41.3%, a reduction of CO₂ emissions by up to 30.8%, and a reduction of avoidable delay minutes up to 89.5%. The corresponding delay cost through a proactive maintenance scheduling approach could be reduced by as much as 99.2%. However, due to the condition-based maintenance approach on a sub-system level, the average aircraft utilization has decreased by up to 4.6 percentage points as the total amount of necessary system cool-down times before maintenance execution is increasing.

We concluded our study by presenting the limitations of the current simulation setup which will need to be addressed in future work. As we have focused in this paper solely on the interaction of aircraft operations and line maintenance, the next development steps will have to include additional stakeholders for the maintenance decision making process. Additionally, an extension of the involved stakeholders will require an adapted prescriptive maintenance algorithm. In order to allow a holistic optimization, this algorithm needs to be able to incorporate (a set of) each stakeholders objectives to derive subsequent maintenance decisions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors. We would like to thank the editors and reviewers for their valuable feedback to improve the quality of this paper.

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