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Evaluation of Prescriptive Maintenance Strategies for a Tire Pressure Indication System (TPIS) assuming Imperfect Maintenance

Masterarbeit

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Evaluation of Prescriptive Maintenance Strategies for a Tire Pressure Indication System (TPIS) assuming Imperfect Maintenance

Master Thesis

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Kurzfassung

Digitale Zustandsüberwachungstechnologien ermöglichen die Ausfallvorhersage von Flugzeugsystemen und werden in Zukunft enorme Auswirkungen auf die Flugzeuginstandhaltung haben. Aktuelle Forschungsarbeiten bewerten das Potential dieser Technologien innerhalb neuartiger präskriptiver Instandhaltungstrategien. Diese Strategien kombinieren zukünftige Ausfallvorhersagen eines Systems mit gegebenen operationellen Umgebungsbedingungen, um den optimalen Zeitpunkt für die Instandhaltung zu identifizieren. Existierende präskriptive Instandhaltungsmodelle vernachlässigen hierbei jedoch den Einfluss der imperfekten Instandhaltung, welcher sich auf die Systemzuverlässigkeit, die Systemverfügbarkeit, sowie die damit einhergehenden Kosten auswirkt. Das Ziel dieser Arbeit besteht darin, zu untersuchen, wie sich dieser Einfluss der imperfekten Instandhaltung auf präskriptive Instandhaltungsstrategien im Rahmen des Reifenüberwachungssystems auswirkt. Zudem wird ein Luftfahrtinstandhaltungs-Stakeholder-Modell für ein Präskriptives-Simulations-Modell des Reifenüberwachungssystems vorgestellt, welches bei zukünftiger Implementierung präzisere Strategieentwicklungen ermöglicht. Dieses Luftfahrtinstandhaltungs-Stakeholder-Modell umfasst die Stakeholder Flugzeuginstandhaltung, Airline, Mechaniker, Logistikdienstleister und Komponenteninstandhaltung. Das imperfekte Instandhaltungsmodell berücksichtigt nicht nur technologische Einflüsse, sondern darüber hinaus auch menschliche Faktoren. Die Einflüsse durch Müdigkeit, Dokumentengestaltungen, Zertifikate, Training, Erfahrung, Alter und Umweltbedingungen werden im Modell einbezogen, um den Grad der Imperfektion einer durchgeführten Aufgabe zu ermitteln. Die imperfekte Instandhaltung betrachtet dabei diskret durchgeführte Reparaturaufgaben und kalkuliert einen neuen Systemzustand nach der Durchführung einer imperfekten Reparatur. Für die Entwicklung von präskriptiven Instandhaltungstrategien des digitalen Reifenüberwachungssystems dienen die Ergebnisse einer Sensitivitätsanalyse, bei der die Parameter der imperfekten Instandhaltung hinsichtlich der Zielgröße Instandhaltungskosten analysiert werden. Diese Instandhaltungsstrategien werden anschließend mit dem aktuellen Prozess der Reifenwartung verglichen, wobei die Anwendung des Reifenüberwachungssystems mit Human-Factor-Optimierung das höchste Einsparungspotential von circa 67 Prozent im Vergleich aufzeigt.

Schlagwörter: Imperfekte Instandhaltung, Präskriptive Instandhaltung, Menschlicher Faktor, Virtual Age Method, HEART.

Abstract

Digital technologies for condition monitoring enable failure predictions of aircraft systems and will have an enormous impact on aircraft maintenance in the future. Current research studies evaluate the potential of these technologies within prescriptive maintenance strategies. These strategies combine failure predictions of a system with given operational environmental conditions to identify the optimal time for maintenance. However, current prescriptive maintenance models neglect the impact of imperfect maintenance, which affects system reliability, system availability and its associated costs. The goal of this thesis is to investigate how this impact of imperfect maintenance affects prescriptive maintenance strategies including the tire pressure indication system. In addition, an aviation maintenance stakeholder model for a prescriptive simulation model of the tire pressure indication system is presented, which will allow for more precise strategy development in future implementations. This aviation maintenance stakeholder model includes the stakeholders aircraft maintenance, airline, mechanics, logistics service providers, and component maintenance. The imperfect maintenance model considers the impact of human factors in addition to technological influences. The effects of fatigue, procedure design, certifications, training, experience, age, and environmental conditions are included into the model to determine the degree of imperfection of a performed task. Imperfect maintenance considers discretely performed maintenance tasks and calculates a new system state after the execution of an imperfect repair. For the development of prescriptive maintenance strategies for the tire pressure indication system, the obtained results of a sensitivity analysis are used. In this context, the parameters of the imperfect maintenance model are analyzed with regard to the objective maintenance cost. These strategies are subsequently compared to the defined state-of-the-art tire maintenance process. In comparison, the application of the tire pressure indication system in addition to human factor optimization indicates the highest cost savings potential of 67 percent.

Keywords: Imperfect Maintenance, Prescriptive Maintenance, Human Factors, Virtual Age Method, HEART.

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Abbreviations

$ABAO$	As Bad As Old	[−]
$AGAN$	As Good As New	[−]
age	Age of a mechanic	[a]
AI	Assessed Impact	[−]
AMM	Aircraft Maintenance Manual	[−]
$CAMO$	Continuing Airworthiness Management Organization	[−]
CBM	Condition-Based Maintenance	[−]
CM	Corrective Maintenance	[−]
CMM	Component Maintenance Manual	[−]
DLR	Deutsches Zentrum für Luft- und Raumfahrt	[−]
E	Engineering	[−]
EC	Environmental Condition	[−]
EL	Experience Level	[−]
EPC	Error Producing Condition	[−]
FC	Flight Cycle	[−]
$HEART$	Human Error Assessment and Reduction Technique	[−]
HEP	Human Error Probability	[−]
$HRAT$	Human Reliability Assessment Technique	[−]
IB	Inside Bright Light	[−]
IF	Inside Faint Light	[−]
II	Inspection Interval	[FC]
IM	Imperfect Maintenance	[−]
IPM	Inspection Method	[−]
LRU	Line Replacement Unit	[−]
M	Maintenance	[−]
MH	Man Hours	[−]
MPD	Maintenance Planning Document	[−]
$MMEL$	Manufacturer Minimum Equipment List	[−]
$MTTR$	Mean Time To Repair	[min]
NC	Number of Certifications	[−]
NHU	Nominal Human Unreliability	[−]

Abbreviations

$OBUC$	Outside Bright Light Comfortable Weather	$[-]$
$OBUW$	Outside Bright Light Uncomfortable Weather	$[-]$
$OFCW$	Outside Faint Light Comfortable Weather	$[-]$
$OFUW$	Outside Faint Light Uncomfortable Weather	$[-]$
PCM	Performance Condition Monitoring	$[-]$
PD	Procedure Design	$[-]$
PE	Proportion of Effect	$[-]$
PM	Preventive Maintenance	$[-]$
PR	Performance Restoration	$[-]$
RC	Reference Configuration	$[-]$
RD	Restoration Degree	$[-]$
RUL	Remaining Useful Lifetime	$[-]$
TAT	Turn-Around-Time	[min]
TL	Training Level	$[-]$
$TPIS$	Tire Pressure Indication System	$[-]$
UTC	Universal Time Coordinate	$[-]$

Latin Symbols

a	Lower tire pressure boundary	[psi]
t	Time	[h/min/s]
n	Current repair	$[-]$
m	Simulation time span	[FC]
A	Degree of restoration	$[-]$
x	Time between repairs	$[-]$
p	tire pressure	[psi]
c	Cost	[\$]
v	Virtual age	$[-]$
b	Upper tire pressure boundary	[psi]
X	Interpolation parameter for performance	$[-]$
Y	Interpolation parameter for PE	$[-]$

Greek Symbols

σ	Standard deviation of pressure checks	[psi]

Indices

$func$	Functional check
$insp$	Detailed inspection
k	Maximum number of assessed impacts
n	Number of repair
$real$	Real
$repl$	Replacement
$rest$	Restoration
x	Number pressure checks

1 Introduction

In this chapter, a brief introduction is given to familiarize the reader with the problem. Moreover, research questions, objectives, and the thesis structure are presented.

1.1 Motivation

Currently, one of the biggest innovation fields in the aviation industry is the digital transformation, including digital technologies for condition monitoring. By equipping aircraft with sensors, these monitoring systems can be utilized to detect the state of various aircraft systems and components. The information gathered is used to assess the aircraft system's health through an early fault detection and the prediction of failures, expressed by the aircraft system's Remaining Useful Lifetime (RUL). Therefore, the application of condition monitoring systems can improve maintenance decisions, reduce operating costs and increase the operational stability. To take full advantage of such a condition monitoring system, appropriate new maintenance strategies have to be developed. (Meissner et al. 2020, p. 1; Meissner et al. 2019, p. 1)

The prescriptive maintenance strategy is a novel maintenance strategy and represents a revision of the predictive maintenance. It takes into account not only the prediction of future events but also the operational environment. (Meissner et al. 2020, p. 2)

A prescriptive maintenance decision support model is a multi-criteria model that incorporates the tasks and objectives of the operational process. The goal of the prescriptive strategy is to optimize the maintenance schedule of the overall process in order to maximize the operational stability, reduce unplanned maintenance activities and their associated negative impacts (e.g. downtime cost) (Nemeth et al. 2018, p. 1040-1041).

1.2 Objective

In a former research project by Nemeth et al., prescriptive maintenance strategies have been developed on the basis of the availability of different parts, components and resources as well as an operational plan (Nemeth et al. 2018). While Meissner et al. made a first attempt to develop a precise stakeholder simulation model to represent the overall maintenance process, the essential stakeholder for the logistic process has been neglected (Meissner et al. 2020). This simulation model was developed at the Institute of Maintenance, Repair and Overhaul in the German aerospace center (Deutsches Zentrum für Luft- und Raumfahrt (DLR)) to evaluate the effectiveness of condition monitoring systems by means of discrete event simulations. Therefore, the first goal of this thesis is to develop a stakeholder model that represents the overall aircraft maintenance process. Within this model, the responsibilities and functionalities of stakeholders are illustrated as well as their respective interactions. This model is created using information gathered from the literature.

Another research gap identified in the models introduced by Meissner et al. and Nemeth et al., is the missing consideration of the impact by imperfect maintenance on the development of prescriptive maintenance strategies (Meissner et al. 2020, Nemeth et al. 2018). Its relevance in maintenance planning has already been illustrated for the:

- Impact of system unavailability and associated costs (Sanchez et al. 2009),
- improvement of system reliability, and (Ben Mabrouk et al. 2016)
- optimal use of available resources (man power, time & budget) (Pandey et al. 2016).

Therefore, developed prescriptive maintenance strategies need to be evaluated with respect to the impact of imperfect maintenance. Hence, the second goal of this thesis is the enhancement of DLR's existing simulation framework by an imperfect maintenance module. The imperfect maintenance module considers human factors and their impact on maintenance.

The functional relationships of the extended simulation framework is verified with the help of an A320's Tire Pressure Indication System (TPIS) use case. The TPIS is a condition monitoring system which could replace routine, hard-time scheduled tire pressure monitoring tasks by automated functional checks. On the basis of a sensitivity analysis, two prescriptive maintenance stra-tegies for the TPIS have to be developed under given framework conditions: A maintenance strategy with TPIS application and a human factor optimized maintenance strategy with TPIS application. These two strategies have to be evaluated and compared against the conventional state-of-the-art tire maintenance process.

1.3 Structure of the Thesis

In the following chapter, basic knowledge about aircraft maintenance is presented. After an overview of the most important maintenance strategies, the use case of the A320 tire pressure maintenance task and the existing simulation framework are elucidated. In order to achieve the goals mentioned above, important aviation stakeholders are presented and an introduction to the topic of imperfect maintenance is given.

In Chapter 3, the basic knowledge about the presented stakeholders is used to propose a maintenance stakeholder model, which enables the evaluation of the TPIS in a more precise surrounding environment. Each stakeholder is transformed into a class with functions and attributes for programming purposes. Next in Chapter 4, the imperfect maintenance model is developed by combining and adjusting existing methods from the literature. In Chapter 5, a parameter study is used to identify the impact of the imperfect maintenance module's parameters on a defined objective. Within this chapter, two prescriptive maintenance strategies for the TPIS are introduced. The strategy showing the highest cost saving potential compared to the state-of-the-art maintenance process is emphasized. Finally, in Chapter 6, a summary of the overall work is given and potential improvements for future research are listed.

2 Fundamentals

The principles of aircraft maintenance builds on the reliability-centered maintenance concept. This approach seeks to maximize the operational safety and reliability while keeping the associated costs low (Gerdes et al. 2016, p. 394-395; Meissner et al. 2020, p. 2).

Aircraft and system manufacturers define tasks and respective intervals for the aircraft and its components to preserve the aircraft's airworthiness continuously. Aircraft systems are subject to regular inspections at fixed intervals or must be exchanged due to exceeding their useful lifetime. These scheduled tasks and intervals are provided by the aircraft manufacturer as an initial maintenance program approved by the aviation authorities. (Ackert 2010, p. 9)

The so called Maintenance Planning Document (MPD) serves the operator as a first point of reference for planning maintenance activities. Within the MPD necessary information for maintenance planning is provided and used by the operator to develop its own maintenance program. (Ackert 2010, p. 9)

Besides tasks and interval specification, the MPD also provides estimated work times and preparation time (Meissner et al. 2020, p. 2-3).

2.1 Basics of Aircraft Maintenance

Every system goes through various stages of deterioration in the course of its life cycle. The measures applied throughout its life, either to extend its life or to ensure its restoration to a functional state, can be summarized under the term maintenance (Kinnison 2004, p. 5).

To prevent the system from deteriorating to an undesirable level, the so called Preventive Maintenance (PM) is applied, which seeks to keep the system in an operational status by frequently restoring the condition of a system before it fails (Kinnison 2004, p. 6). PM is scheduled or applied on the basis of prescribed criteria to minimize the failure probability of the system or to minimize the restriction of the system's functionality (Hoelzel & Schiling 2014, p. 43).

Scheduled maintenance which is often used in connection to the PM procedure consists of maintenance actions conducted on a regular scheduled basis i.e., in aviation on a daily, flight hour or flight cycle (consisting of a take-off and a landing) basis (Kinnison 2004, p. 6). Once the system is in the undesired deterioration level meaning an non-operational system level, the so called Corrective Maintenance (CM) has to be applied (Kinnison 2004, p. 6). In this case, the system is restored after fault detection to a state in which a required task can be performed properly (DIN 2010).

In contrast to scheduled maintenance, unscheduled or unplanned maintenance is maintenance conducted at an unpredictable time (Kinnison 2004, p. 7). It refers to the elimination of damages or malfunctions which are identified during functional checks, routine testing, inspections or flight operations (Hinsch 2019, p. 195).

As explained above, there are two main maintenance strategies: PM and CM. These main strategies can be subdivided further into subcategory strategies as illustrated in Figure 2.1 (Ahmadi 2010, p. 15-16).

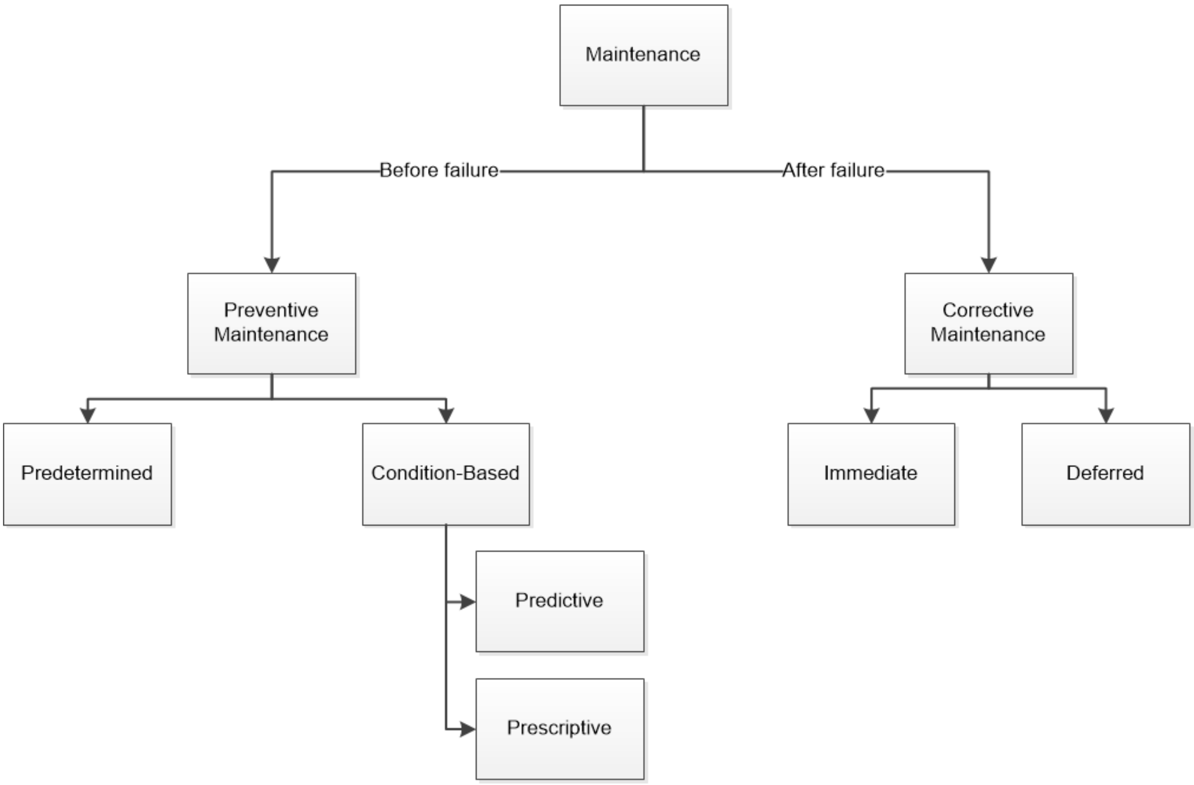


Figure 2.1: Overview of maintenance strategies (adapted from (Ahmadi 2010, p. 15))

Figure 2.1 shows an overview of the most commonly used maintenance strategies, extended by relevant maintenance strategies for this thesis: Predictive and prescriptive maintenance. In addition to that, further maintenance strategies can be found in (DIN 2010).

Predetermined maintenance is conducted on prior established time intervals or according to a fixed number of used units without prior condition assessment. These intervals are established in dependency of the system's failure mechanism. In contrast to that, for a Condition-Based Maintenance (CBM) strategy, maintenance decisions are made in dependency on the monitored state of the system. (DIN 2010, p. 22)

Generally, the state can be measured by condition monitoring systems and/or inspection and/or functional checks to determine the deterioration level of the system and consequently derive further necessary maintenance actions (DIN 2010, p. 22; (Ahmadi 2010, p. 15)).

A special case of condition monitoring is predictive maintenance which is based on a forecast or prognosis of the system's failure. The failure prediction can be estimated by analyzing the system properties that characterize the system's deterioration. (DIN 2010, p. 23)

Condition monitoring systems are used to receive the prognosis of the remaining useful lifetime which can be determined by continuous measurements and assessments of the system's state. Critical parameters are then used to determine the optimal maintenance time in respect to failure and wear prediction. (Feldmann et al. 2017, p. 3)

Another particular case of condition monitoring is prescriptive maintenance. The prescriptive maintenance strategy is an advanced version of the predictive maintenance strategy (Meissner et al. 2020, p. 2). The optimal maintenance time is found under the consideration of failure forecasts and operational surrounding processes (Meissner et al. 2020, p. 2). Corrective maintenance is either carried out immediately after fault detection in order to avoid unacceptable consequences or deferred according to predefined maintenance rules (Hoelzel & Schiling 2014, p. 43).

In practice, aircraft maintenance is divided into base-, line- and shop-maintenance, which are explained in more detail in Subsection 2.4.

2.2 A320 Tire Pressure Maintenance Task

Aircraft tires are checked regularly and restored when necessary in order to ensure the aircraft's safety and maintain tire's health (Bill et al. 2019, p. 90). The tire manufacturer recommends a cool down time of three hours after landing and before measurement to receive reliable results (Meissner et al. 2020, p. 7). Pressure measurement results are distorted if the tire gas has not reached the ambient temperature (Meissner et al. 2020, p. 7).

Due to a high frequency of these scheduled tire pressure checks as well as a low complex integration of the tire degradation model, the tire pressure maintenance is a suitable use case to compare an automated condition monitoring system to the conventional inspection procedure (Meissner et al. 2020, p. 6). A wireless tire pressure maintenance approach as proposed by Bill et al. can improve the hard time tire pressure measurement from 15 to 1 min per aircraft (Bill et al. 2019). Recorded tire pressure data can be transmitted wireless via Bluetooth connection to ground support equipment (Bill et al. 2019, p. 97). The mechanic can view the tire pressure on a technical device and decide, if further actions (e.g. re-inflate) are necessary (Bill et al. 2019, p. 90). Hence, the tire pressure check task remains unchanged, however the task will be conducted with the help of a technical device which makes the task less time consuming and less susceptible to errors. The manual pressure check requires a mechanic who reads the pressure value on the respective tire using a pressure gauge (Goodyear 2020, p. 14).

As stated above, the tire pressure task consists of a scheduled maintenance task which is the tire pressure check and dependent on the tire's condition different unscheduled maintenance tasks can follow. The tire pressure check is scheduled in time intervals of three days which can be found in the MPD of the A320 use case (see Table 2.1).

Table 2.1: Tire pressure scheduled task for an A320 (Meissner et al. 2020, p. 2)

Dimension	**Value**
Description	Wheels: Functional check of tire pressures
100 % Interval	3 days
Men	1
Task MH	0.10
Prep. MH	0
Access MH	0
Applicability	All

A premature pressure check is also possible within the three day interval, but the deadline shall not be exceeded. Moreover, Table 2.1 contains estimated work hours (Man Hours (MH)) for the task, preparation time and time needed for access. Also, an approximated number of workers required to execute the job and for which aircraft configuration this is applicable is given. Note that the MH are approximated indicators, which can differ from the time needed in reality. The MPD serves operators as a first point of reference for planning the maintenance tasks. Within the MPD, unscheduled maintenance tasks which subsequently may follow are neglected. For this use case, these unscheduled maintenance tasks can follow separately or in combination:

- Tire restoration, meaning re-pressurization or depressurization of the tire,
- replacement of wheel or replacement of multiple wheels from axis, and/or
- additional intensive inspection.

Furthermore, each tire is replaced by an overhauled or completely new tire every 250 FC (Michelin 2020).

2.3 Simulation Framework

The Institute of Maintenance, Repair and Overhaul in Hamburg-Finkenwerder of the German Aerospace Center (DLR) has developed a simulation framework, which allows the evaluation of the effectiveness of condition monitoring systems and the expected operational influences by means of discrete-event simulation. This simulation framework is integrated in Python 3.8 to enable open source standards (Meissner et al. 2020, p. 7).

The framework is an agent-based simulation environment in which several agents are called during the course of the simulation to either generate required information or execute necessary functions of the simulation (Meissner et al. 2020, p. 7). This environment is created with object-oriented programming, where each agent represents an object, i.e. an instance of a class. Hence, each agent possesses a certain number of attributes and functions inherited from its class. The agents or objects rely on information provided by user input including the flight rotation plan, maintenance parameters and condition monitoring technology parameters (e.g. thresholds or measurement intervals) (Meissner et al. 2020, p. 7). A simulation time span can be determined in which the aircraft is continuously operated and maintained (Meissner et al. 2020, p. 8). A simplified simulation sequence is depicted in Figure 2.2 and the simulation framework is given in Figure 2.3.

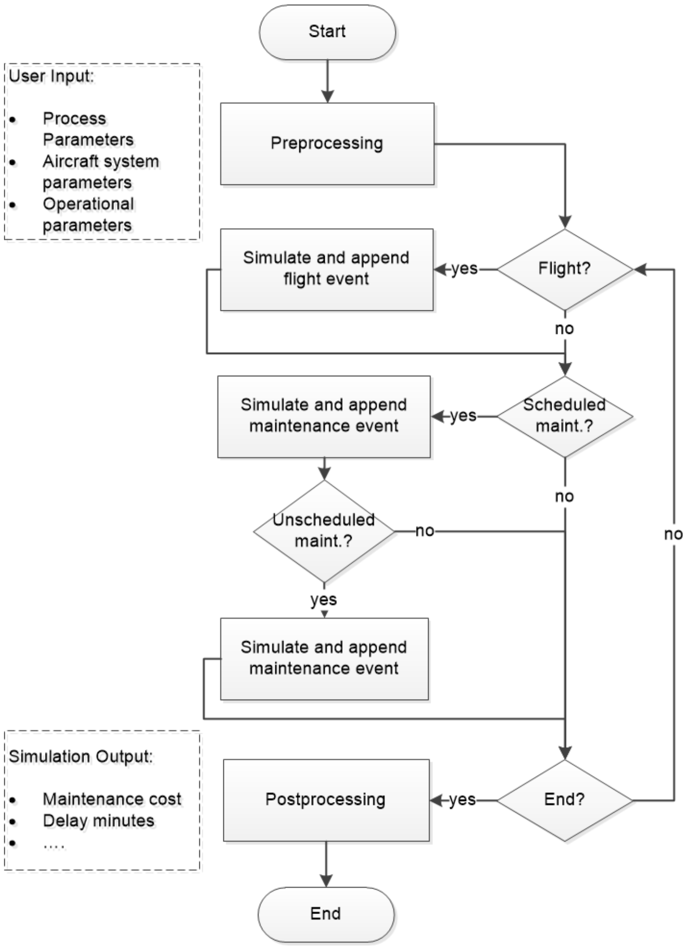


Figure 2.2: Simplified simulation sequence

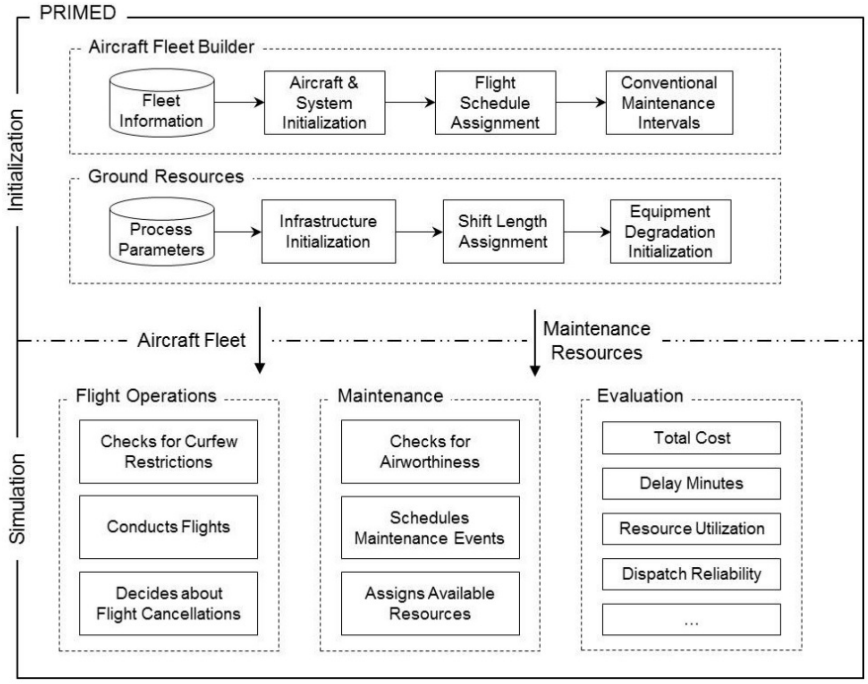


Figure 2.3: Simulation framework for prescriptive maintenance strategy development (Meissner et al. 2020, p. 8)

In Figure 2.3, the respective agents and their responsibilities are illustrated. Simulation input parameters can be divided into three groups (Meissner et al. 2020, p. 7):

- Process parameters i.e. maintenance hub and maintenance task parameters ,
- aircraft system parameters i.e. scheduled maintenance parameters, (e.g. threshold, cool down time or system's nominal condition) and
- operational parameters i.e. aircraft fleet and operating parameters.

After the initialization of the objects, all agents are assigned with an individual timestamp in Universal Time Coordinate (UTC) format and are passed into a continuous loop which terminates when reaching the simulation time span. Events which occur during the simulation will be recorded in the respective agent's event calendar. The sequence of simulated operations or maintenance activities are chosen with respect to the aircraft's timestamp. (Meissner et al. 2020, p. 7-8) This sequence is simplified in Figure 2.2. Currently the simulation framework is limited to the use case of the tire pressure maintenance task which is used for the evaluation of the effectiveness of the tire pressure indication system. However, the expansion to other systems can be easily implemented due to the agent-based simulation environment.

2.4 Aircraft Maintenance Stakeholder

The stakeholders of aircraft maintenance are composed of the participating aviation parties. In this thesis, an aircraft maintenance stakeholder is defined as an organization or party that determines and influences the maintenance scheduling process. In Figure 2.4, an overview of the tire pressure maintenance process is depicted. This process includes scheduled and unscheduled tasks and serves as template for the general maintenance process that any aircraft system will pass to a different extent. Actions which are conducted within this process are assigned to the respective stakeholder responsible for the action. With the help of this method, the aircraft maintenance stakeholders can be identified.

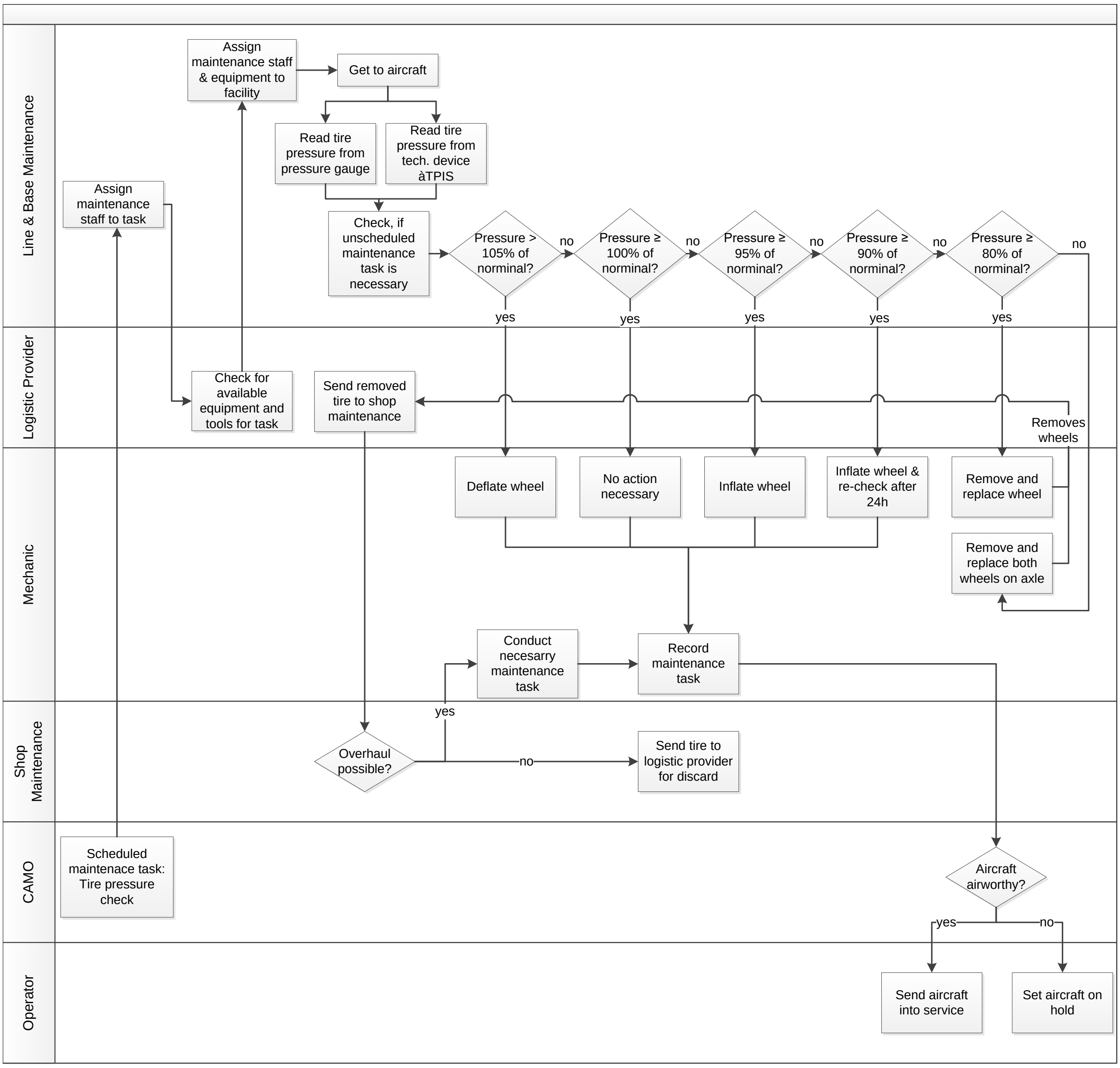


Figure 2.4: Tire pressure task process addressed to aircraft maintenance stakeholder

The tire maintenance process starts with the scheduled maintenance task, i.e. the tire pressure check. First, the assignment of the respective mechanic to the envisaged task takes place. Then, the availability of equipment needed is checked. Next, mechanic and equipment are assigned to the designated maintenance facility. The mechanic will either check the tire pressure by using the pressure gauge or in the case of an aircraft integrated TPIS by reading from a technical device. In dependence to the determined tire pressure condition, following maintenance tasks can be conducted: restore the tire meaning deflate or inflate the tire, restore and inspect the tire within 24 hours, change the tire or multiple tires from the axis or no actions will be necessary. If an exchange of the wheel is required, the tire will be sent to the logistic provider in order to be routed to an appropriate shop for repair. Next, the maintenance task is recorded by the mechanic. Following, the aircraft's airworthiness is measured, resulting in the decision if an aircraft is sent back to service or is put on hold. In the following, the maintenance stakeholder's general tasks and responsibilities are summarized.

2.4.1 Operator and Continuing Airworthiness Management Organization

The operator or airline is an organization which manages the transportation of passengers and cargo by aircraft (Cambridge University Press 2020). This organization has different tasks, challenges and responsibilities.

The airline flight operation department is accountable for safety and efficiency of the flight service and to generate revenue for the organization. This includes the management of flights including flight crews, maintenance and ground personnel. (Belobaba 2009, p. 2012) The airline's profitability is influenced by the development of flight schedules which should include beneficial flight times in profitable markets (Lohatepanont Manoj 2002, p. 19; Bazargan 2010, p. 31). The airline planning process is simplified in Figure 2.5.

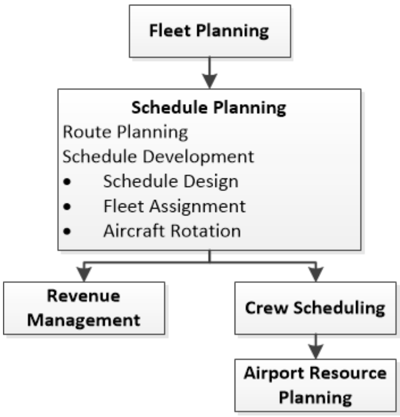


Figure 2.5: Overview of simplified Airline Planning Process (adapted from (Lohatepanont Manoj 2002, p. 21))

In fleet planning, which is the first step of the complex planning process, the airline decides which types and how many aircraft are intended to be sent into operation either through leasing or buying. The decisions made in this state of planning require estimations of demand, revenue and cost information or high quality data for detailed prediction of future scenarios. The focus lays on the scheduling of passenger allocations to maximize potential profitability. Due to great differences in time horizons, the fleet planning decision is not integrated into the remaining planning process. Next steps therefore build on a given fleet family (set of aircraft from the same type). (Lohatepanont Manoj 2002, p. 20-22)

The airline's schedule planning process starts with route development. The airline decides which markets, i.e. origins and destinations, have to be approached with respect to predicted world-wide demand (Lohatepanont Manoj 2002, p. 22). This route structure will then be improved or overhauled for the changing environment and demands in the schedule development. The schedule development includes three major areas (Lohatepanont Manoj 2002, p. 21; Papakostas et al. 2010, p. 605):

1. Schedule design, where a list of flight legs (origin and destination) is determined with departure and arrival times,
2. fleet assignment, where the available aircraft types, which the airline operates, are assigned to flight legs and
3. aircraft rotations, where aircraft (by tail numbers) are assigned to maintenance integrated routes (set of flight legs).

The aircraft rotation is of particular interest for maintenance planning. Through an optimized maintenance integrated route planning, undesired delays can be prevented (Belobaba 2009, p. 184). These undesired delays are connected to delay costs borne by the airliner (Gerdes et al. 2016, p. 11). Therefore, a major goal of the airline operator is its aircraft's operability (Papakostas et al. 2010, p. 605). The appearances of unscheduled maintenance can cost delays and cancellations, if they cannot be resolved in time (Papakostas et al. 2010, p. 605).

With the defined fleet schedule, the tasks revenue management, crew scheduling and airport resource planning arise. Revenue management aims to maximize the revenue for the given fleet schedule by considering differential pricing and seat inventory control (Lohatepanont Manoj 2002, p. 25).

The different pricing approaches cover the willingness to pay for low fare passengers as well as high fare passengers. Price differences are given by offering different services with different limitations at different prices. The seat inventory control aims to restrict the low-fare-seats, so that passengers booking later can only purchase higher fare-seats. (Lohatepanont Manoj 2002, p. 26)

The crew scheduling aims to assign flight crews (pilots and/or flight members) to flights with respect to certain constraints given for instance by the pilot which is only allowed to fly specific aircraft types or flight crew's restriction of the maximum flying time or minimum rest times

(Belobaba 2009, p. 202).

The airport resource planning aims especially at managing gate allocation, ground personnel scheduling and slot allocation (Lohatepanont Manoj 2002, p. 28). Further and more detailed information of the airline business and the overall planning process can be found in (Belobaba 2009; Lohatepanont Manoj 2002).

To ensure continuous airworthiness of aircraft the Continuing Airworthiness Management Organization (CAMO) has to be commissioned. This aviation legislation approved organization is a link between the maintenance organization and the aircraft operator in order to manage and supervise the rule of continuing airworthiness and its associated activities. Additionally, CAMO has the responsibility to perform airworthiness reviews to be able to verify and renew airworthiness certificates. In general the aircraft operator carries out the tasks given by CAMO. Nevertheless, a subcontracted approved organization can also take over the responsibilities. (Hinsch 2019, p. 33)

2.4.2 Aircraft Maintenance: Line- and Base Maintenance

For aircraft maintenance activities, a distinction is made between on-aircraft maintenance and off-aircraft maintenance (Kinnison 2004, p. 141). In Figure 2.6, the respective maintenance activity categories are illustrated. Additionally, the coherent process between on-aircraft maintenance, logistics and off-aircraft maintenance is depicted.

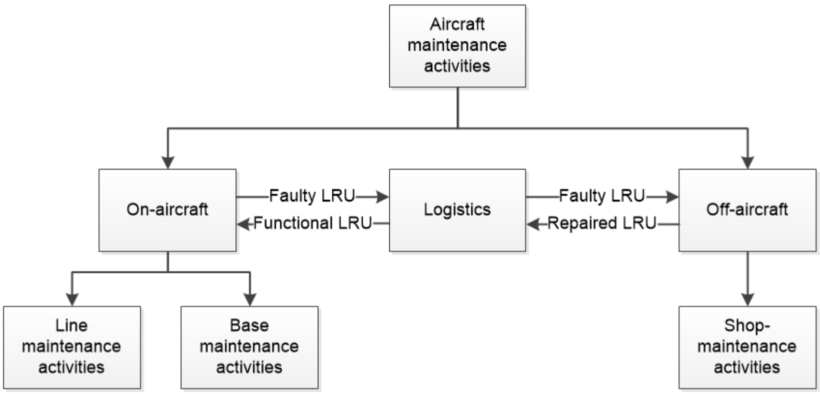


Figure 2.6: Categories of Maintenance Activities (Kinnison 2004)

To minimize flight delays, the aviation industry has introduced the concept of Line Replacement Units (LRU). Within on-aircraft maintenance, components or systems which most commonly intend to fail can quickly be removed and replaced with functional units. These faulty units are sent to logistics to be either discarded or routed to appropriate shops for repair (see Figure 2.6). (Kinnison 2004, p. 12, 141)

The reference to on-aircraft activities is used when maintenance is conducted on the aircraft (Kinnison 2004, p. 141). The category off-aircraft is referred to maintenance activities conducted on components, units or equipment dissembled from the aircraft (Kinnison 2004, p. 141). These maintenance activities are conducted in shop maintenance which will be discussed in Subsection 2.4.3. Furthermore, the responsibilities of the logistic provider will be explained in Subsection 2.4.4. On-aircraft activities are distinguished further into line and base maintenance (Kinnison 2004, p. 141).

In base maintenance, hangar and dock facilities are mandatory for conducting maintenance tasks while line maintenance tasks can be conducted on terminals or ramps. Line maintenance seeks to preserve existing conditions while base maintenance includes overhaul tasks to restore the aimed conditions. (Papakostas et al. 2010, p.604; Hinsch 2019, p. 193)

Any maintenance tasks that can be carried out on the aircraft without taking it out of service is referred to as line maintenance (Kinnison 2004, p. 143). The process of line maintenance is reduced to the turn-around-time (TAT) to guarantee the aircraft's next dispatch on time (Papakostas et al. 2010, p.604). Line maintenance activities for instance include post-flight inspection, components replacement or routine checks that can take place during turn-around, transit or night stops (Papakostas et al. 2010, p.604). Here, the most important decision to take is a GO or NOGO decision depending on the Manufacturer Minimum Equipment List (MMEL), which contains the minimum number of critical components that are obliged to ensure proper functionality (Papakostas et al. 2010, p.604). Based on the MMEL, s deferral of maintenance tasks to a successive airport with more suitable resources, are allowed (Kinnison 2004, p. 151). If MMEL requirements are met, the aircraft receives a GO status meaning it's approval for the next flight. This decision process highly depends on the discovery of unscheduled maintenance tasks (Papakostas et al. 2010, p.604).

Line maintenance is either performed at outstation, i.e. off-base, or at the home base of an airline. Deferral of maintenance actions will most likely be taken at outstations due to limited personnel or skills, limited availability of parts and supplies or limited capacity within the hangar or stands. Outstations have to be provided with necessary parts and supplies that are needed to perform maintenance. (Kinnison 2004, p.151)

The makeup of the line maintenance personnel considers the organization of shifts (number of shifts and shift lengths) in regard to the scheduled flights, aircraft types, work types, and amount of work (Kinnison 2004, p.153).

Contrarily, base maintenance or heavy maintenance is referred to maintenance tasks performed when the aircraft is out of service. It is associated with intensive major maintenance tasks or modifications or maintenance events that exceed the TAT. To minimize the resulting aircraft downtime, any base visit contains an extensive combination of different necessary maintenance activities. Parts and supplies as well as tools and equipment needed for the maintenance tasks are provided within the hangar. Big airlines can be equipped with several hangars while smaller airlines only operate one base hangar. (Kinnison 2004, p. 155-156)

The facility capacity can vary by the type and size of aircraft (two- or four-engine, narrow- or wide-body etc.) and number of aircraft that fit in the hangar. In order to accomplish the hangar maintenance on time, the hangar visit has to be scheduled, planned and controlled. (Kinnison 2004, p. 156) Due to the higher complexity of base maintenance activities, base maintenance employees are qualified to conduct line maintenance but line maintenance employees are not qualified to conduct base maintenance (Hinsch 2019, p. 193).

2.4.3 Shop Maintenance

Overhaul shops are responsible for the maintenance of components and equipment that have been dissembled from the aircraft by on-aircraft (line and base) personnel (see Figure 2.6). The removed system is marked for maintenance and sent to logistics to either discard the unit or route it to the appropriate component shop for repair. (Kinnison 2004, p. 165-166)

Component shop activities can be assigned in-house or to a third party. Restored units are marked as serviceable and returned to the logistic organization where the units are stored for future operations. Maintenance activities in shop maintenance range from simple cleaning to complete overhaul of the systems. (Kinnison 2004, p. 165-166)

Off-maintenance always takes place on off-service basis. Typically, maintenance shops have a spare parts area which is maintained by logistics. Beside work and spare areas, maintenance shops have areas to separately store non-functional, serviceable as well as discarded components. Moreover, maintenance shops are equipped with tools and special equipment necessary for the work. An important objective for shop maintenance is the Mean Time To Repair (MTTR). (Kinnison 2004, p. 168)

There are various types of overhaul shops that can be found by MRO providers, airlines or component manufacturers that for instance include avionic shops, mechanical shops or engine shops (Kinnison 2004, p. 165).

Mechanical shops can consist of one system or be a combination of multiple systems depending on airline size and requirements. These shops would include for example pneumatic systems, hydraulic systems and oxygen systems. The wheel, tire and brake shop for instance offers the following services :

- Disassembly, assembly and repair of wheels,
- servicing, retreating and repair of tires, and
- replacement and adjustment of brakes. (Kinnison 2004, p. 167)

Information about tasks and responsibilities of further specific overhaul shops can be found in (Kinnison 2004, p. 165-168).

2.4.4 Logistic Provider

The logistic provider is the link between on-aircraft (base and line) maintenance and off-aircraft (shop) maintenance (Kinnison 2004, p. 151).

The logistic organization is accountable for providing supplies and parts for base and line maintenance, outstations as well as component maintenance, to maintain an appropriate inventory of parts and supplies and to place these on suitable locations for quick access of the maintenance personnel. These activities have to be conducted under legitimated budget constraints. (Kinnison 2004, p. 169-170)

The logistic organization consist of four divisions (Kinnison 2004, p. 170):

- Inventory control,
- stores,
- purchasing as well as
- shipping and receiving.

The inventory control has the task to ensure the availability of parts and supplies at appropriate locations for shop maintenance and on-aircraft maintenance. Therefore, the necessary stock level has to be established and appropriate reorder times have to be determined. Changes within the fleet, of aircraft conditions or operational conditions have to be considered for the stock level adjustment. (Kinnison 2004, p. 169-170)

Stores have the responsibility to exchange and deliver parts to the respective mechanics. They make sure that parts and supplies are properly stored and repairable units are routed to the appropriate maintenance shop. (Kinnison 2004, p. 170)

Products under warranty are routed to the manufacturer or designated facilities for warranty repair. Furthermore, stored parts or equipment have to be checked on expiration dates (if applicable). (Kinnison 2004, p. 175)

Purchasing deals with suppliers and manufacturers for the procurement of parts and supplies. Shipping and receiving is responsible for all shipments in and out of the airline as well as packing and unpacking of goods and inspection of the received goods. (Kinnison 2004, p. 170-171)

The highest expenses within an MRO organization are presented by the logistic provider. To manage this financial burden, the logistic provider has to manage its inventory proactively in dependence of different conditions. (Kinnison 2004, p. 169)

The logistic organization has to take into account that with aging system or equipment the need for spare parts increase. Furthermore, stock level at selected locations continually have to be adjusted for real maintenance activities. The necessary stock for maintenance can also vary in different seasons. The maintenance quality is strongly influenced by the established stock level. (Kinnison 2004, p. 176)

There are two major problems with the stock level. One case is the overstocking by airlines to minimize downtime, cancellations and delays but risking having supplies that will not be needed or that will become out-of-date. The other case are airlines which store a minimal amount of spare parts to minimize the cost needed to run the airline. With regard to the latter, this approach has the disadvantage of high risks for maintenance downtime and delays or cancellations, also associated with dissatisfied customers and even poor quality maintenance. Hence, the optimal stock level is a major challenge for the logistic provider. (Kinnison 2004, p. 176-177)

2.4.5 Mechanics

Mechanics or technicians are trained to know how aviation systems operate and work. In base- or shop-maintenance they can be specialized on particular systems such as avionic systems or mechanical systems. Mechanics of line maintenance may be specialized to address all systems. Usually mechanics follow procedures for repair, troubleshooting and fault isolation which is provided by job cards developed and maintained by the engineering department. Within the job cards, the procedure and necessary equipment for the task are provided. (Kinnison 2004, p. 65) Additionally, mechanics have the responsibility to record conducted work within the job cards (Kinnison 2004, p. 194).

Also, removal, installation as well as testing procedures are provided for the mechanics. All of these procedures are standardized. Experienced Mechanics have the skill to identify the root of the problem and work effectively. (Kinnison 2004, p. 101-102)

Mechanics have to be properly trained and licensed in general aviation maintenance as well as on the system they are responsible to maintain (Kinnison 2004, p. 54). Therefore, mechanics undergo continuous formal and practical training provided by the airline in order to sharpen their skills (Kinnison 2004, p. 83).

Aircraft mechanics can be licensed under the following categories (Hinsch 2019, p. 265):

1. Category A: Certified mechanic for line maintenance
   Mechanics certified according to category A can perform minor line maintenance.

   CAT A licensed personal is entitled to release certificates of personally accomplished tasks that are specified on his or hers task list.
2. Category B1: Certified technician - Mechanical
   B1 certified technicians are entitled to perform maintenance on aircraft structures, engines, mechanical, electrical systems as well as simple avionic replacements. CAT B1 also includes the CAT A license. Moreover, technicians certified according to B1 license are authorized to carry out and certify the task carried out by themselves as well as to release maintenance work performed by another person.
3. Category B2: Certified technician - Avionics
   A CAT B2 license entitles to perform and certify maintenance work on avionics and electrical systems. The category B2 license does not cover any A category qualifications.
4. Category C: Certified engineer - Base Maintenance
   A certified category C engineer is entitled to issue release certificates for the entire aircraft after base maintenance. Category C engineers are responsible to check if necessary maintenance tasks are successfully completed by CAT B1 and B2 technicians.

CAT A, B and C are basic licenses which have to be obtained by aviation authorities. Category B and C are further extended with specific type ratings which allow the mechanic only to repair specific aircraft types (configuration and engine specifications) that are exhibited by the company. (Hinsch 2019, p. 265; European Union Aviation Safety Agency 2020, p. 451-452)

2.5 Imperfect Maintenance

Maintenance can be classified by the degree of restoration the item can receive. These classifications are as followed (Pham & Wang 1996, p. 426):

a) Perfect maintenance or repair which refers to maintenance actions that restore the condition level to "As Good As New" (AGAN). The system possesses the same failure rate and lifetime distribution as a completely new system. Generally, the replacement of systems are considered as perfect repair.

b) Minimal maintenance or repair which refers to maintenance actions that restores the condition level to "As Bad As Old" (ABAO). The system possesses the same failure rate as it had prior to failing. For instance, when one non-dominating faulty component of many is exchanged by a new one.

c) Imperfect Maintenance (IM) or repair refers to maintenance actions that can be considered between the extremes of AGAN and ABAO. The system condition will not be AGAN but younger.

d) Worse maintenance or repair refers to maintenance actions that increase the failure rate or system's age. Hence, the system condition worsens instead of improving.

e) Worst maintenance or repair refers to maintenance actions that lead to system's breakdown or failure.

In practice, maintenance actions that can lead to imperfect, worse, and worst repair for instance include repairing the wrong part, incorrect condition assessment, performing maintenance actions that are not necessary but optional due to tight schedules, human errors or replacements with non-functional parts (Pham & Wang 1996, p. 426).

PM as well as CM can be classified as perfect, minimal, imperfect, worse, and worst repair. The restoration degree of perfectness which is applied in practice highly depends on requirements such as costs, reliability, and safety. In many studies after PM and CM, the system is assumed to be perfect (AGAN) or minimal (ABAO). This assumption is not applicable for a multi-component system such as aircraft where safety and reliability standards are extremely high. Hence, maintenance actions applied on aircraft bring the system to a level between AGAN and ABAO. (Pham & Wang 1996, p. 426-427)

2.5.1 Imperfect Maintenance Modeling Methods

A wide range of imperfect maintenance treatment methods have been presented in the recent years. An overview of some imperfect treatment methods are given in Table 2.2.

Table 2.2: Imperfect maintenance methods (Pham & Wang 1996, p. 427-431; Carlo & Arleo 2017, p. 343-347)

(p, q)-rule	(p(t), q(t))-rule	Improvement Factor
After maintenance (corrective or preventive), system's condition level returns to AGAN (perfect repair) with probability p and to ABAO (minimal repair) with probability q=1-p. Imperfect maintenance is referred as general maintenance possessing two special cases: minimal and perfect maintenance. For p=1 maintenance corresponds to perfect while p=0 it corresponds to minimal. Hence, degree of restoration is adjustable by p. Repair time is neglected.	Extended (p,q)-rule with age-dependent system time. Perfect repair is considered with probability p(t) and minimal repair is considered with probability q(t)=1-p(t), where t represents item's used age (time between failure and last perfect repair). Degree of restoration is adjustable by p(t). Repair time is neglected.	Assumption of changing system time interval to younger or newer condition but not to zero (complete new). Failure rate after PM is assumed to be between perfect and minimal. The restoration degree in failure rate is given by the improvement factor. The improvement factor can be approached with cost or system's age functions or by expert judgment.
(α, β)-rule	**Shock model method**	**Virtual age method**
Lifetime of system will decrease by the fraction α of the lifetime prior to repair event, with $0 < \alpha < 1$. Hence, with increasing number of repairs the lifetime decreases. Furthermore, the (α, β)-rule considers an increasing repair time with increasing number of repairs. The repair time therefore is multiplied by β with $\beta > 1$ each time of repair.	System or component is subject to random damage or shocks in time. The random damages are added to the current damage level and between the time intervals the damage level stays unchanged. Imperfect maintenance is applied to reduce the damage level with $100(1-b)\%$ from the total level, where $0 \leq b \leq 1$. The extreme cases of minimal repair is given by b=1 and perfect repair is given by b=0. Degree of restoration is adjustable by b.	Virtual age represents the restoration level the system can achieve after repair. Kijimi developed this approach and assumed that the system's state after maintenance can be given by the virtual age $V \geq 0$, which is equal or smaller than the actual system's age v (age without damage). The assessment of failure intensity is approached by adjusting the system's virtual age instead of considering the operational time.

Further methods or advanced methods of the ones mentioned above can be viewed in (Pham & Wang 1996, p. 427-431; Carlo & Arleo 2017, p. 343-347). These proposed imperfect maintenance models can be classified into various maintenance policies (Wang 2002, p. 470). In Figure 2.7 an overview of the maintenance policies which are mostly applied in practice is given (El Khalfi et al. 2017, p. 6).

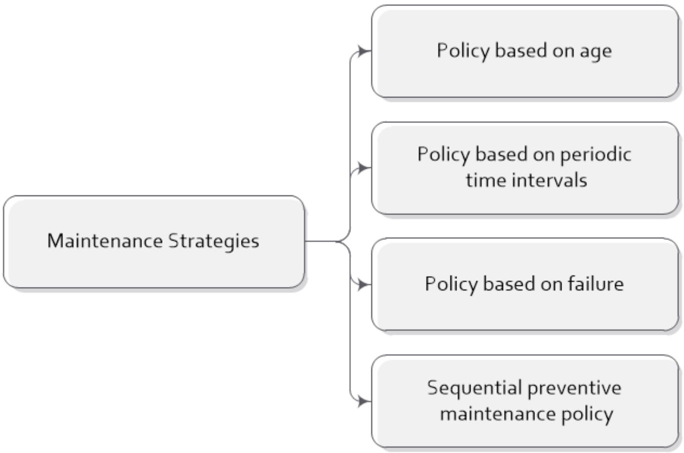


Figure 2.7: Overview of frequently used maintenance strategies (adapted from (El Khalfi et al. 2017, p. 6))

Policy based on age: Age-dependent policies include numerous numbers of imperfect maintenance models, if either one or both PM and CM are imperfect. Many studies of these policies can be found in literature. Within the age-dependent PM model, an item is maintained at a specific lifetime T or restored after a breakdown, whichever occurs first.

Policy based on periodic time intervals: A wide range of maintenance policies based on time can be found in literature. Within the periodic PM policy, maintenance is conducted on predetermined time intervals kT with $k = 1, 2, ...$ and components or systems are restored at intervening points of failure. In the periodic PM policy, "periodic replacement with minimal repair at failure", components are replaced at kT and failures are restored by minimal repair. Another approach assumes PM to be imperfect at every T, intervening failures to be minimal repaired and components may be replaced at a specific number of PMs.

Policy based on failure: Within the failure limit policy, it is assumed that PM is conducted when a predetermined specific failure rate or reliability level of the component is reached and correction activities take place when it fails.

Sequential PM policy: In contrast to periodic PM, in sequential PM policy, components are maintained under variable time intervals. In practice, frequency of maintenance increases with aging components, therefore maintenance intervals are shortened with passing time, which can be represented with the sequential PM policy.

For more information on the respective maintenance policies refer to (El Khalfi et al. 2017, p. 6; Pham & Wang 1996, p. 433-436; Wang 2002, p. 470-481). Note, that maintenance models can be based on one or multiple maintenance policies with the objective to minimize costs, maximize availability or minimize downtime (El Khalfi et al. 2017, p. 7).

2.5.2 Human Factors in Maintenance

Humans play an important role during the performance of aircraft maintenance, since human error can contribute to disruption of operations or can lead to system and equipment damages. A simple description of human error is the failure to perform a specific task, which can either lead to damage or the non-fulfillment of the operational schedule. Basically, errors in maintenance occur by wrong preventive activities or wrong repair. With aging equipment or system, the occurrence of errors increases due to high maintenance frequency. (Dhillon & Liu 2006, p. 22)

According to Dunn, it has been identified that after maintenance has been carried out, over 50% of systems fail prematurely (Dunn 2007). In aviation, maintenance and inspection jobs are complex and vary in an environment with difficult ambient conditions, time pressure, and lack of sufficient feedback (Dhillon & Liu 2006, p. 23). Some typical maintenance errors identified in the industry are (Dhillon 2014, p. 1-2):

- Backward installed parts,
- incorrect use of greases or lubricants,
- failure due to specific instruction and procedures,
- failure due to time constraints, workload or priorities, and
- failure resulting from unfinished tasks due to shift change.

To illustrate the impact of human factor in aircraft maintenance, Allen et al. consider the technician's work environment as a human factor system model (Allen & Rankin 1997, p. 1186). This model is depicted in Figure 2.8.

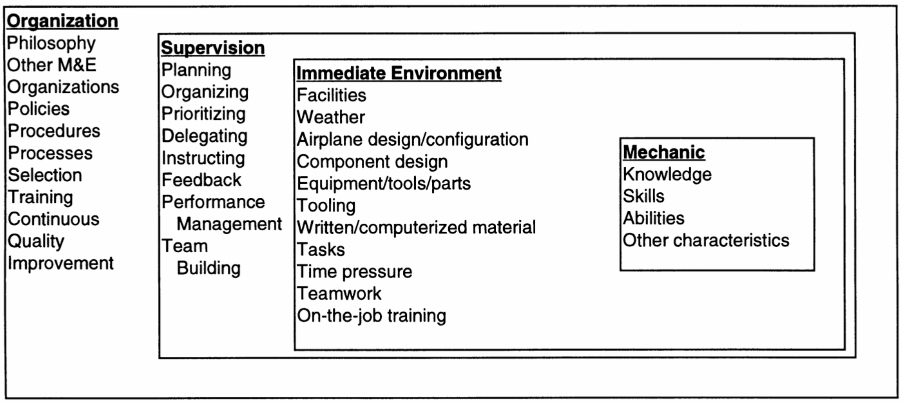


Figure 2.8: Human Factors System Model based on Technician's Work Environment (Allen & Rankin 1997, p. 1186)

Figure 2.8 demonstrates the four basic human factor categories that influence the mechanic's performance. Beginning with the inner category, the mechanic performance is shaped by his knowledge, skills, abilities, and further characteristics that are required to successfully fulfil the task.

Knowledge includes airline process, system and task knowledge. Skills as well as abilities are composed by important competencies to conduct maintenance such as troubleshooting or replacement and removal of a part or component. Further characteristics such as willingness to pursue jobs with high quality, motivation for hard work, capacity for teamwork or being assertive are characteristics which are more difficult to detect. (Allen & Rankin 1997, p. 1186)

The second human factor category is the immediate environment of the mechanics. This category includes for instance, the design of facilities (e.g. noise, lighting conditions), the weather (e.g. for ramp or terminal maintenance), the aircraft configuration (e.g. changing requirements of task), components design, written procedures (e.g. user friendly or complex), the task itself (e.g. efficient or error-vulnerable) and equipment, tools as well as parts. Moreover, factors such as teamwork, time pressure as well as training is included within the immediate environment. (Allen & Rankin 1997, p. 1186)

The third category reflects supervisors or managers that provide instructions or know-how for the mechanics. The supervision impacts the mechanic's performance by planning, organizing, prioritizing, delegating of tasks, instruction or feedback. A manager's goal is to motivate mechanics and encourage team work using performance management and processes to provide continuous quality improvement. (Allen & Rankin 1997, p. 1187)

The last category reflects the maintenance and engineering (M&E) organization. The organization influences mechanics by factors such as responsibilities taken by other M&E organization (e.g. by planning, ordering, written procedures, developing job cards). Moreover, the organization philosophy has an impact on the mechanic's performance by providing airline procedures, policies or maintenance processes. The organization is also responsible to hire technicians and developing job description or training programs for the employees which are all factors that influence the mechanic performance. (Allen & Rankin 1997, p. 1187)

3 Maintenance Stakeholder Model

In this chapter, a maintenance stakeholder model is introduced, to capture the diverse interests of participating parties. This model serves to evaluate the TPIS within its environmental conditions and is based on the literature research summarized in Section 2.4. In order to evaluate prescriptive maintenance strategies for the TPIS, the developed model needs to consider discrete flight simulations and maintenance related micro processes.

In the following section, the modules of the stakeholder model and their interactions are presented. Hence, the interfaces between the modules that have to be implemented within a simulation framework are given. In the next section, the implementation of this model with the class definition of each stakeholder, i.e. agent, is shown .

3.1 Stakeholder Interactions within a Simulation Framework

In this section, the developed stakeholder model for programming purposes is introduced. Besides the identified stakeholders, the following graph includes the imperfect maintenance module which is described in Chapter 4. Five stakeholders have been identified for the model: Operator (including CAMO), aircraft maintenance, logistic provider, shop maintenance, and mechanic. In Figure 3.1, an overview of the developed stakeholder model is given.

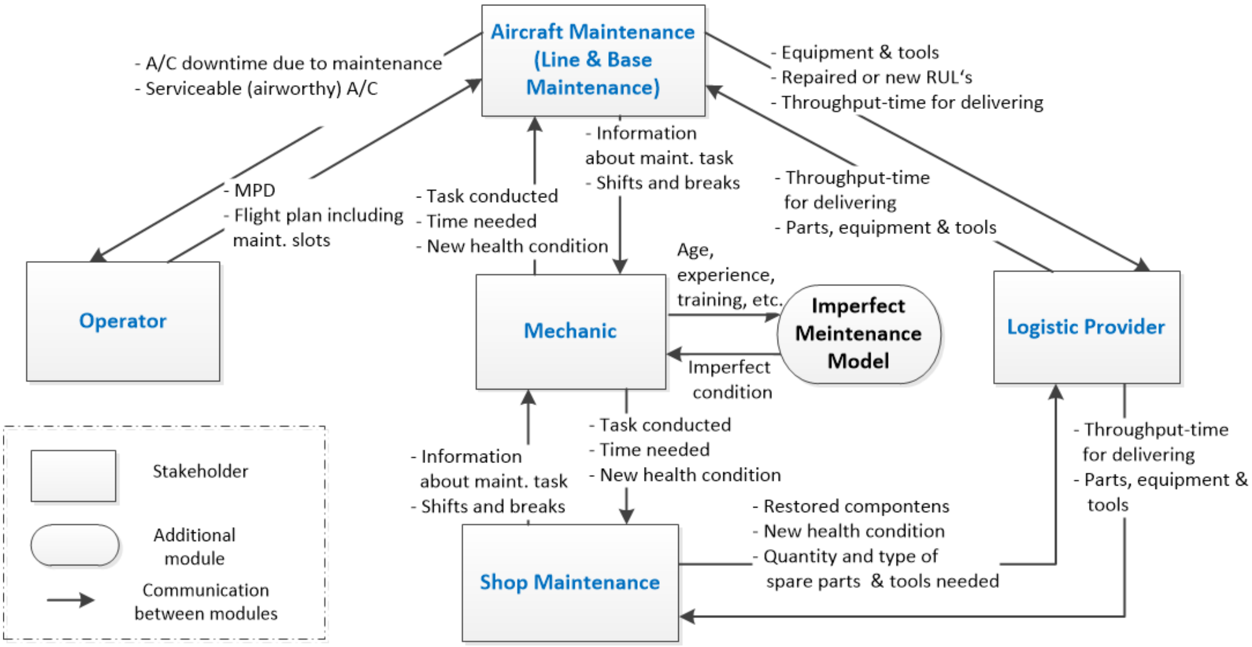


Figure 3.1: Developed aircraft stakeholder model for DLR's simulation framework

The arrows between the stakeholders and the imperfect maintenance module show the communication and interaction between them. While some stakeholders communicate directly with each other, there are also stakeholders who interact through an intermediary stakeholder. An example of an intermediary stakeholder is the logistics provider. The LRUs are first sent by aircraft maintenance to the logistic provider. The logistic provider is then responsible to route the systems to appropriate shops and to store the systems until they are ready for shipment. In reality, the depicted chain of communication in Figure 3.1 can vary depending on the size of the airline and maintenance organization. These depicted interactions or communications are assumed for the model in order to simplify the reality for programming purposes. The communication is illustrated by multiple information and material exchange on the respective arrows. With a more detailed analysis of each stakeholder and the actual implementation of the model in Python the listed enumerations of data exchange, presented in Figure 3.1, can be extended. The implementation of the stakeholder model can be achieved through the class definitions of the individual stakeholders introduced in Section 3.2.

In this model, the logistic provider has to interact as well as link with the shop and aircraft maintenance. Operator and aircraft maintenance are connected by exchanging information with regard to the maintenance program and flight plan including possible maintenance slots. The imperfect maintenance module is connected to the mechanic and intends to determine a task's performance efficiency. Moreover, the mechanic is connected to shop maintenance as well as aircraft maintenance which illustrates the dependency of the staff and the organization for which the employee is hired.

Currently, the stakeholders *operator*, *CAMO*, *aircraft maintenance*, and *mechanic* are implemented within the DLR's simulation framework. Additionally, the stakeholders *shop maintenance* and *logistic provider* have been identified in the literature. By adding these stakeholders, the operational environment of aviation maintenance can be represented more precisely and therefore, more realistic maintenance strategies can be derived. The dependency between on-aircraft maintenance (base and line), logistics and off-aircraft maintenance (shop maintenance) has already been described in Subsection 2.4.2. This dependency is essential to describe an established maintenance organization (Kinnison 2004, p. 141-142). Moreover, this threefold dependency is reflected in a large repair and overhaul company such as Lufthansa Technik. Lufthansa Technik offers services in line, base, and component maintenance. To ensure the provision of an excellent repair service, the logistic service is also included in their portfolio (Lufthansa Technik Logistik Services 2020).

The extended stakeholder model depicted in Figure 3.1 is essential to produce reliable prescriptive maintenance strategies under the assumption of imperfect maintenance. Shop maintenance is currently not considered in the simulation framework. By the implementation of the shop maintenance agent, the maintenance process of a tire after being dissembled from the aircraft can be examined. This process can also be utilized to illustrate the impact of imperfect maintenance within the shop floor process. Up to now, the tire system and its maintenance are integrated within the simulation framework, however more complex systems, such as engines, are mainly serviced in workshops. To be able to additionally integrate a complex system, such as the engine, within the simulation framework, the integration of the shop maintenance stakeholder is necessary for future development.

3.2 Stakeholder Class Definitions

As described in Section 2.3, the DLR's simulation framework models an agent-based environment in which each agent is either responsible for generating information or performing actions. In this section, an advanced agent-based environment for the DLR's simulation framework is created by defining an individual class with important functions and attributes for each stakeholder.

In the following, specific stakeholder goals are introduced. Functions and attributes necessary to implement the goals on a maintenance related basis within the advanced simulation framework are presented. The goals, functions and attributes have been developed using the literature research summarized in Section 2.4. The presented functions, and attributes can be extended, if the individual stakeholders are examined in more detail.

Since the stakeholders *operator*, *CAMO*, *aircraft maintenance*, and *mechanics* are already implemented within DLR's simulation framework, the functions and attributes of these classes are partly taken from the existing model and expanded by further identified relevant methods and attributes from the literature.

3.2.1 Class Definition Aircraft Maintenance

One specific goal of line maintenance is to reduce its process to the TAT in order to guarantee the aircraft's next dispatch on time. This goal has to be fulfilled by quick maintenance actions which do not exceed the TAT, by replacing non-functioning systems with functional ones and by deferring maintenance tasks to a facility station with more suitable resources to handle the task. For this purpose, first the aircraft maintenance agent needs to provide information, whether the approached facility is homebased or off-based (outstation). Depending on this information, the agent needs to predict the time necessary to perform a task. More elaborate maintenance tasks are usually performed at the homebase which is characterized in the model by providing better resource availability and needing less time for maintenance. Moreover, the agent needs to provide information about the available mechanics and equipment of all stations in order to evaluate, if a dispatch can be achieved on time. When a maintenance task has to be performed, the agent has to assign the task to an available mechanic. The mechanics have to be assigned to their respective shifts by the agent in order to determine which mechanic is available. Additionally, if a LRU is removed by line maintenance, the agent has to route the required unit to the logistic provider.

One specific goal of base maintenance is to minimize aircraft downtime resulting from hangar visits. In order to minimize the aircraft downtime within the simulation framework, the agent has to provide information about the facility availability and the hangar capacity. The hangar can be defined by the agent for specific aircraft types. In the simulation framework, aircraft downtime is influenced by the number of available mechanics and equipment defined for the specific hangars. Moreover, it has to be checked for which maintenance tasks a mechanic is certified. With this information, the agent then calculates the downtime of an aircraft when comparing different combinations of maintenance tasks possible during the hangar visit. Within the simulation framework, the mechanics are assigned to work and therefore are no longer available for other maintenance tasks.

The aircraft maintenance agent has to ensure that appropriate breaks have been taken before the next shift starts. Within the simulation framework, maintenance actions are assumed by the agent as restoring the airworthiness of an aircraft. Each facility is assumed to contain a specific number of equipment and tools. The subsequent supply of additional tools and equipment is conducted by the agent through an order from the logistics provider agent.

The information and actions explained above are summarized as functions and attributes in Table 3.1.

Table 3.1: Overview of the functions and attributes of the aircraft maintenance agent for programming purposes

Aircraft maintenance agent (base & line maintenance)	
Attributes	Functions
• Mechanics (objects created from the mechanic agent class) • Equipment • Facility station (e.g. homebase/outstation) • Facility type (e.g. apron, hangar, terminal) • Facility availability • Facility capacity • Aircraft types for facility • Certification (base and/or line maintenance)	• Assign on-aircraft maintenance tasks to staff • Assign staff to shift • Assign maintenance task & staff to facility • Check, if staff is eligible to return to duty (min. time between shifts) • Calculate aircraft downtime due to maintenance • Order tools & equipment from logistic provider • Send non-functional/non-serviceable units to logistic provider • Check, if unscheduled maintenance task has to be conducted • Restore aircraft‘s airworthiness • Replace non-functional unit with functional unit • Defer maintenance action to subsequent maintenance station or homebase

3.2.2 Class Definition Operator

In reality operator and CAMO are two different organizations, however in this model the operator includes the responsible actions and information provided by CAMO in order to restrict the number of classes to be developed.

Since a large airline, such as Lufthansa, has their own CAMO team which is able to issue certificates of airworthiness, such an assumption is reasonable (Lufthansa Technik 2020).

One specific goal of the airline operator is to ensure the aircraft’s operability. In order to keep aircraft in service, the aircraft’s airworthiness has to be maintained and delays have to be avoided. To simulate the operation of aircraft and to meet the goal of performing flights continuously, the following functions and attributes have to be implemented.

First, to make the airworthiness of a fleet assessable, the aircraft and its component conditions have to be deteriorated by the operator agent. Within the advanced simulation framework, the operator agent provides a fixed flight plan for the aircraft as well as information about necessary airport restrictions such as non-operating hours and the minimum turn-around-time. Flight events are recorded by the agent for subsequent evaluation. Delay cost resulting from exceeding the given maintenance time slots have to be determined by the operator agent. The operator agent checks, whether the flight can be conducted or curfew restriction of the respective airport is violated by a departure. Since only airworthy certified airplanes can be sent to the next flight, the operator agent also checks if the airworthiness requirements are met. Further airworthiness related functions of the operator agent include the check of scheduled maintenance tasks according to the MPD as well as allowing the deferral of maintenance tasks according to the MMEL. The attributes and functions for the agent operator are summarized in Table 3.2.

Table 3.2: Overview of the functions and attributes of the operator agent for programming purposes

Operator agent	
Attributes	Functions
• Flight plan • Non-operating hours • Minimum turn-around-time • Maintenance program (e.g. MPD) • MMEL	• Deteriorate aircraft & its components • Operate aircraft according to flight plan • Record flight events • Check, if departure is allowed or if aircraft is in non-operating hours of airport (e.g. curfew restrictions) • Calculate delay costs • Check, if scheduled maintenance is due • Approve or reject airworthiness of aircraft • Determine, if for scheduled task deferral is allowed • Send aircraft into service

3.2.3 Class Definition Logistic Provider

One goal of the logistic provider is to maintain an appropriate stock level, which provides enough supplies to minimize downtime, cancellations and delays and at the same time reduces inventory to minimize cost.

To pursue both goals, the logistic provider agent needs to provide a list of stored units, parts, equipment and tools. With this list a total inventory can be derived from which the storage cost can be calculated.

If parts or equipment are no longer usable or have already been shipped to shop maintenance, aircraft maintenance or outstations, the existing inventory list has to be updated. The limited service life of parts and equipment is represented by the shelf lives provided by the logistic provider agent. LRU which are sent to the logistic provider by aircraft maintenance are routed to appropriate shops. Once the repaired unit is returned from shop maintenance, this system will be stored as a functional unit prepared to be routed to aircraft maintenance when needed. Stored products under warranty are sent by the logistic provider to the manufacturer or designated facilities for warranty repair.

The discussed responsibilities and actions associated to the goals of the logistic provider are summarized in Table 3.3.

Table 3.3: Overview of the functions and attributes of the logistic provider agent for programming purposes

Logistic provider agent	
Attributes	Functions
• List of stored units, parts, equipment & tools (item & quantity) • Time required to deliver order • Capital & storage costs • Shelf life of parts or equipment • Stock buffer	• Send equipment, tools and parts to aircraft, & shop maintenance • Check, if shelf life is exceeded • Ship parts and equipment to outstation • Calculate delivery costs • Determine necessary inventory stock • Calculate storing cost • Update stock level • Send LRU to shop maintenance • Recceive and stocks LRU • Send products under warranty to manufacturer or designated facilities for warranty repair

3.2.4 Class Definition Shop Maintenance

One important objective of shop maintenance is the mean time to repair. In order to implement this objective within an advanced simulation framework, the shop maintenance agent needs to provide information about its mechanics team, equipment, and facility. The availability of mechanics and equipment as well as the shop capacity is decisive to determine the mean times to repair in the model. To find the appropriate shop for each maintenance task, the shops have to be distinguished into engine, avionic, electrical and mechanical shops by the shop maintenance agent. In order to simulate the conducted maintenance task, a mechanic has to be assigned to the facility and the task which has to be conducted. Within the model, during the entire maintenance process, the mechanic is not available for further tasks, facility capacity is reduced and equipment or tools used for the task are not available. Whether a received LRU can be restored or has to be discarded is decided by the shop maintenance agent. The agent is also responsible for ensuring the mechanics take their breaks between shifts. These breaks must be taken into account, as a system is not being maintained during that time. The actions and information discussed above are translated into functions and attributes for a class definition in Table 3.4.

Table 3.4: Overview of the functions and attributes of the shop maintenance agent for programming purposes

Shop maintenance agent	
Attributes	Functions
• Mechanics (objects created from the mechanic agent class) • Equipment • Facility availability • Facility capacity • System certification • Shop type (engine shop, avionic shop, electrical shop, mechanical shop)	• Assign off-aircraft maintenance tasks to staff • Assign staff to shift • Assign maintenance task & staff to facility • Check, if staff is eligble to return to duty (min. time between shifts) • Calculate mean time to repair • Order tools & equipment from logistic provider • Restore system‘s airworthiness • Decide, if LRU has to be restored or discarded

3.2.5 Class Definition Mechanic

Since an error committed by a mechanic can have fatal consequences in aviation, the goal of the mechanic is to minimize his errors. The frequency of faults and the accuracy with which a mechanic works can be determined using the following characteristics of the mechanic: experience level, training level, and age. How the mechanic's characteristics are used to calculate his accuracy is explained in Chapter 4.

Depending on the type and number of certificates the mechanic possesses, he can perform several maintenance tasks. The mechanic has to be assigned with the certifications he possesses to make sure that he is allowed to do the work he is assigned to. To avoid possible errors, the mechanic works with job cards, Aircraft Maintenance Manual (AMM), Component Maintenance Manual (CMM), and further procedures.

In order to be able to trace the source of an error, recording the performed task is very important and also required by the aviation authorities. Therefore, it is the mechanic agent's responsibility to record all tasks. In this model, the accuracy of tools and equipment decreases with use. Their deterioration have to be recorded by the mechanic agent. Nevertheless, the accuracy and reliability can be restored by the agent through calibration or replacement with a new component. A list of the translated functions and attributes for the mechanic's class definition can be found in Table 3.5.

Table 3.5: Overview of the functions and attributes of the mechanic agent for programming purposes

Mechanic agent	
Attributes	Functions
• Experience level • Training level • Age • Shifts • Availability • Certifications • Job cards / AMM / CMM / Additional Procedures	• Degrade tools & equipment • Conduct maintenance task • Record maintenance activity (time needed, task conducted) • Calibrate tools

4 Imperfect Maintenance Model

The IM model is developed for the DLR's agent-based simulation framework. Within this simulation framework, maintenance tasks are discretely simulated during operations. These tasks are currently performed under the assumption of perfect maintenance. The model to be developed shall be able to provide information about the system's condition after a conducted maintenance task. This should be done by classifying each tire pressure maintenance task into perfect or imperfect repair. Figure 4.1 depicts the development process of the IM model, which is discussed in more detail in the following sections.

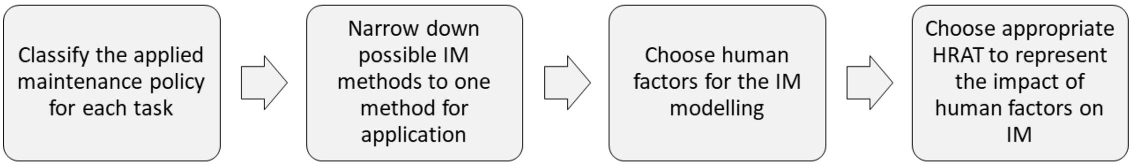


Figure 4.1: Development steps for the IM model

In Section 4.1, one suitable IM method is selected for the IM model. For that purpose, the maintenance actions of the tire pressure control task are classified into appropriate maintenance policies from the policies introduced in Subsection 2.5.1. Due to given simulation framework requirements, one maintenance method of Table 2.2 will be chosen to represent IM. In Section 4.2, human factor categories are selected from which parameters are derived for the implementation in the IM model. Next, in 4.3 an appropriate Human Reliability Assessment Technique (HRAT) is chosen to model the impact of human factors and human's unreliability for IM.

4.1 Imperfect Maintenance Methods

The tire related maintenance tasks integrated within the DLR's simulation framework are as follows:

- tire pressure check,
- tire pressure restoration, i.e. tire inflation,
- detailed inspection and tire pressure restoration, and
- tire replacement.

According to Section 2.2, the tire pressure check is scheduled on every third day. In respect to the measured pressure, the maintenance tasks inflate, intensive inspection or replacement can follow. Additionally, each tire is replaced by an overhauled or completely new tire every

250 FC. Therefore, the four listed tasks can be classified as "policy based on periodic time intervals" in which a system is maintained at specific time intervals and restored at intervening points of failure (see also Section 2.5). This maintenance policy can be modeled by each treatment method introduced in Table 2.2. While IM methods such as (p,q)-rule, improvement factor and (α, β)-rule focus on failure rate changes after imperfect repair, the virtual age method introduces a fictive age to show the impact of IM. (Pham & Wang 1996, p. 427-430) This so called virtual age can easily be transformed to describe the system's condition after a maintenance action. Moreover, the effective age method seems to be preferred in recent studies such as (Jacopino et al. 2006, Dietrich & Kahle 2006, Bartholomew-Biggs et al. 2009). For these reasons, the effective age method will be selected to calculate the impact of imperfect maintenance on the tire.

4.1.1 Effective Age Method Adapted to Tire Restoration Task

Preventive maintenance is applied to expand the useful lifetime of a system and hence reduce the criticality of failure occurrences. Each maintenance action has an effect on the age of the repairable system. The effective age model utilizes a so called virtual age to illustrate these effects and the restoration level that a system achieves after a repair. After maintenance, the virtual age of a system can be less than or equal to its real age. Maintenance treatment is seen as rejuvenation of the system when considering imperfect or perfect repair. There are two main virtual age types introduced by this model. (Carlo & Arleo 2017, p. 345; Bartholomew-Biggs et al. 2009, p. 1-2)

For virtual age type one, it is assumed that damage occurred between last ($n-1$) and current maintenance (n) can be restored. The virtual age type one can be determined as followed (Carlo & Arleo 2017, p. 345):

$$v_n = v_{n-1} + A \cdot x_n \tag{4.1}$$

where v_n is the virtual age after the nth repair, A is the degree of restoration with $0 \leq A \leq 1$ and x_n represents the time between nth and ($n-1$)th repair. The extremes $A = 1$ and $A = 0$ correspond respectively to a minimal and a perfect maintenance. The virtual age is reduced after each maintenance action by $A \cdot x_n$. (Bartholomew-Biggs et al. 2009, p. 2-3; Pham & Wang 1996, p, 430)

In Figure 4.2 the impact of perfect, imperfect, and minimal repair is illustrated.

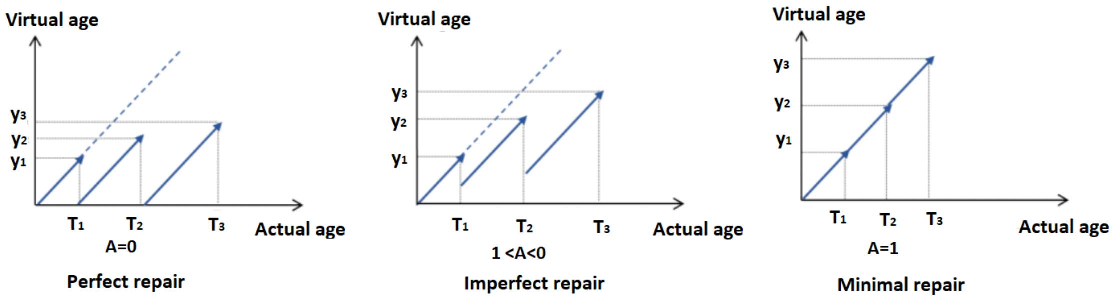


Figure 4.2: Degree of restoration (adapted from (Carlo & Arleo 2017, p. 345))

In contrast, virtual age type two repairs the cumulative damage of current as well as previous damages over the system's lifetime. The nth virtual age according type two is calculated as stated below (Carlo & Arleo 2017, p. 345 Pham & Wang 1996, p. 430):

$$v_n = A_n(v_{n-1} + x_n) \tag{4.2}$$

where A_n is the nth restoration degree and can take random values in the interval $[0, 1]$ for $n = 1, 2, 3, ...$. Also, the extreme $A_n = 1$ and $A_n = 0$ correspond to a minimal and to a perfect maintenance, respectively. The method explained above shall be adapted for the tire restoration task. (Pham & Wang 1996, p. 430)

In this work, the virtual age of the system will be expressed through the total tire pressure of one tire. Each time the tire is inflated one of the two virtual age types explained above have to be applied. Type one would assume that only the tire pressure loss between the last and previous restoration can be restored, i.e. any previous losses cannot be compensated, while type two assumes that the total pressure losses over the complete operation can be restored. With type one, the initial pressure condition can never be achieved as long as at least one imperfect maintenance occurs. Therefore, virtual age type two is used to implement imperfect maintenance for the tire restoration task, for which the possibility to restore the tire pressure to its initial condition can be granted.

Excessively low or high pressure inflation will be considered as reduction of the tire pressure after maintenance, since both cases will reduce the overall age of the tire due to a higher or unequal wear (Michelin 2016, p. 503-504; VERIVOX 2020). An incorrect or inappropriate tire pressure leads to a more frequent maintenance in reality.

4.1.2 Modeling Tire Pressure Check with Normal Distribution

The tire pressure check does not include any restorative action, nor is it very likely to cause damage to the tire. For this reason the virtual age method is not suitable to represent the imperfectness of the tire pressure check. The tire pressure check has, above all an impact on the decision, if an unscheduled task has to follow. Incorrect reading of the pressure value leads to an incorrect decision for the following unscheduled maintenance action e.g. premature refilling or premature replacement of the tire as well as a late intervention in case a maintenance action was demanded. For this reason, the imperfect tire pressure check is simulated with a normal distribution where the expected value represents the real tire pressure and the standard deviation reflects the imperfectness. A typical normal distribution is depicted in Figure 4.3.

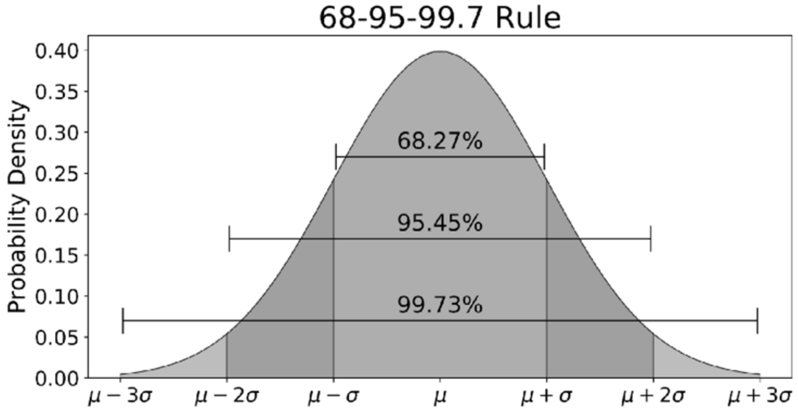


Figure 4.3: Normal distribution (Galarnyk 2018)

In Figure 4.3, it can be seen that 68 % of observations or values are within one standard deviation σ, 95 % of the values or observations are between two standard deviations 2σ and 99 % of the values or observations are between three standard deviations 3σ (Galarnyk 2018). It is assumed that an inaccurately measured tire pressure check lies within the interval $[a_x, b_x]$, where the real pressure is the center of both values:

$$p_{real} = \frac{b_x - a_x}{2} \tag{4.3}$$

As mentioned above, the real tire pressure will be illustrated by the expected value ($\mu = p_{real}$) of the normal distribution. To cover 99.73 % of all possible data, the upper boundary (b_x) will be set to $\mu + 3\sigma$ and the lower boundary (a_x) will be set to $\mu - 3\sigma$. Hence, the standard deviation can be calculated with:

$$\sigma = \frac{b_x - a_x}{6} \tag{4.4}$$

This adapted normal distribution is used to generate a random variable or pressure within the predetermined interval for each conducted pressure check. The degree of restoration is given by σ. In Figure 4.4 two normal distributions with the same expected values (means) and different standard deviations are depicted.

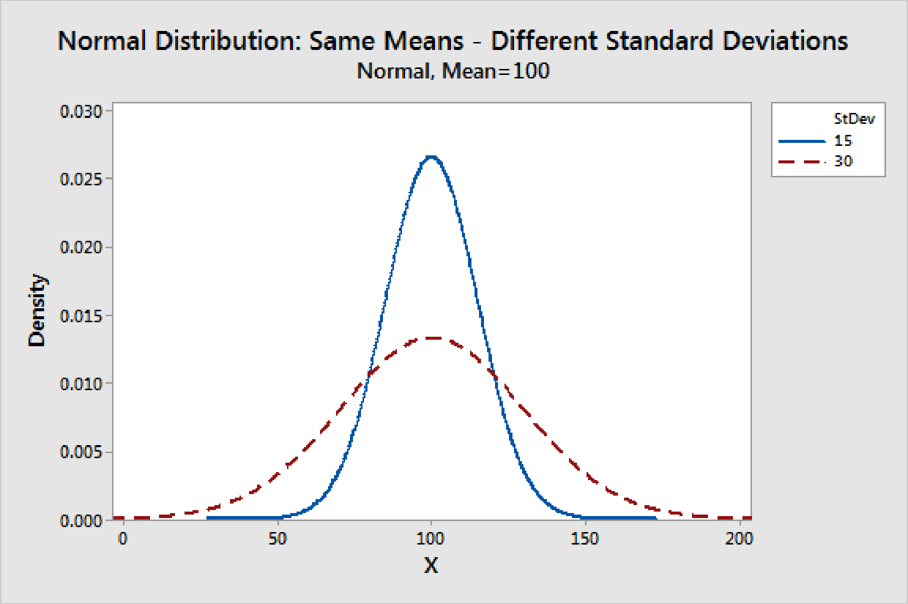


Figure 4.4: Forms of normal distribution (Frost 2018)

A higher standard deviation will lead to a wider spread of possible values while in the case of a smaller standard deviation most values are very close to the mean and thus to the actual tire pressure. Accordingly, a smaller standard deviation represents a closer solution for a perfect repair, while a higher standard deviation has a higher probability of producing imperfect solutions.

4.2 Human Factor Categories for the Imperfect Maintenance Model

There are multiple human factor categories that can be considered for the IM model. In Subsection 2.5.2 the human factors have been distinguished between four super categories:

1. Organization,
2. supervision,
3. immediate environment, and

4. mechanic.

In the scope of this thesis, the focus is on the latter two super categories. From this, multiple categories are selected and parameters for the IM model are derived (see Figure 4.5).

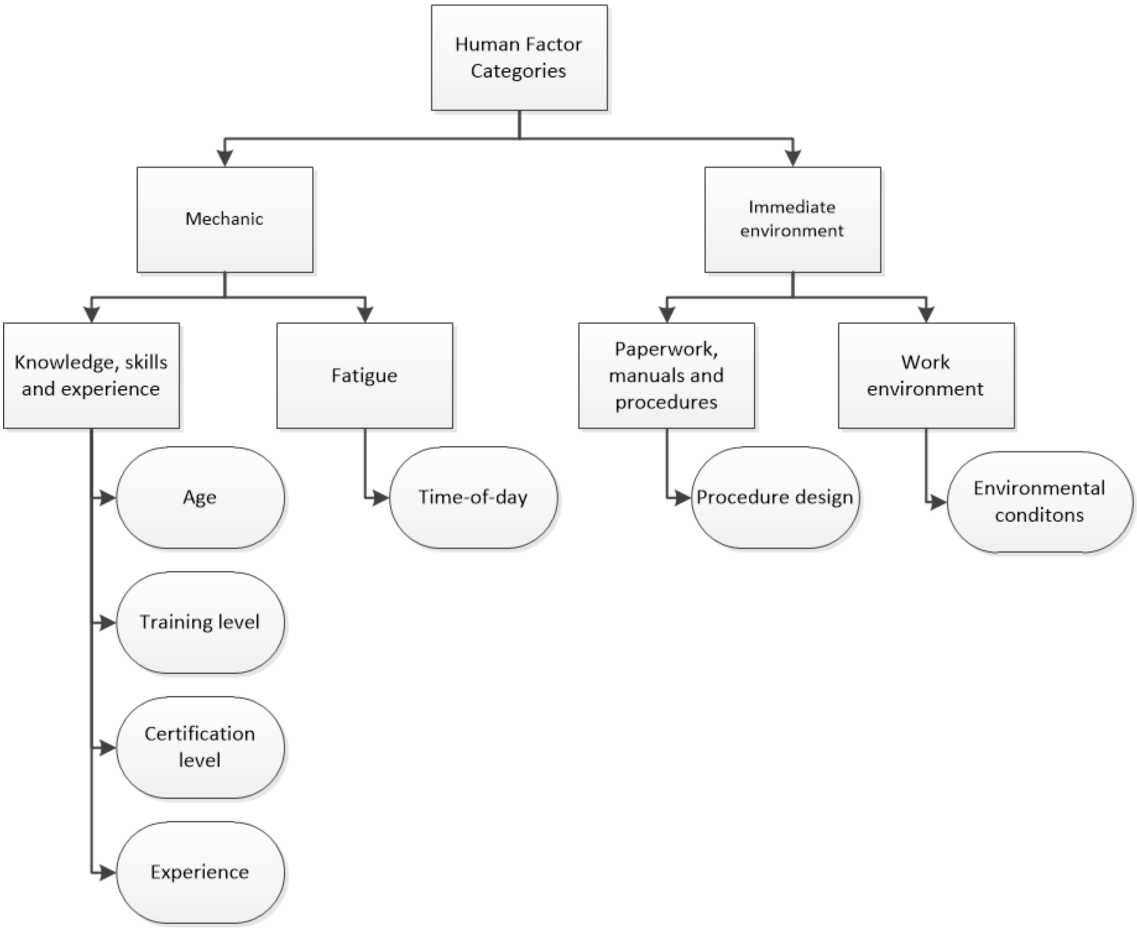


Figure 4.5: Human Factor parameters

Figure 4.5 shows the four considered human factor subcategories for the IM model and below these the respective parameters are presented. In the following, these categories and the intended parameters to be implemented will be explained.

Work environment

Aircraft maintenance is performed under three different environments:

a) Workshops (components),

b) hangars (complete aircraft), and

c) open air, i.e. on apron or ramp (line maintenance).

Depending on the given environment, the mechanic is exposed to different environmental conditions which have an impact on his performance. These are, among others: restricted work spaces, heat, cold, humidity, poor lighting, and low airflow circulations, which all contribute to poor performance. In comparison to hangar work, line maintenance is performed in a much busier working environment and is additionally subject to all variations of weather and lighting conditions. (International Civil Aviation Organisation 2003, p. 36-37)

Knowledge, Skills and Experience

This category is associated with performance reduction due to unfamiliarity with aircraft type or defect as well as lack of skills, training, and experience for the task (International Civil Aviation Organisation 2003, p. 41). Several studies have identified that increasing training activities result in a higher performance efficiency (Tamkin 2005, p. 9).

The age of a mechanic can be associated with higher working experience. On the other hand, higher stress and fatigue levels are reached with increasing age compared to younger workers, which results in a higher risk of incidents. An aging mechanic is exposed to higher stress levels, especially under unfavorable environmental conditions, such as heat, noise, lighting, vibration and visual conditions at night (Schlick et al. 2018, p. 86-87). Moreover, cognitive performance decreases with age (Bell & Williams 2017, p. 7).

Fatigue

The category fatigue will exclusively be presented by the biological clock, also known as human biorhythm. It has been shown that a higher number of accidents occur in very early hours, which is around 2 to 3 am, while the lowest number of accidents occur in late morning which is around 10 to 12 am (International Civil Aviation Organisation 2003, p. 47-48, 38). The biorhythm is often represented by the alertness level. A reduction in alertness level or increase in fatigue will result in a performance decline (Maddox n.d., p. 38) (Health and Safety Executive n.d.).

Paperwork, Manuals and Procedures

This category considers poorly written procedures, e.g. missing or inconvenient information, poor layout of manuals or job cards as well as a higher complexity to perform a task due to multiple additional relevant materials (International Civil Aviation Organisation 2003, p. 41). In fact, many human factor errors in the aviation sector can be related to poorly designed procedures (Drury n.d., p. 1-2). In order to reduce incidents and accidents related to poorly designed procedures in aircraft maintenance, guidelines, and recommendations regarding a better design are given, which can be reviewed in (Drury n.d.).

4.3 Human Error Assessment and Reduction Technique

Human factors play a major role in aviation accidents nowadays (see Figure 4.6).

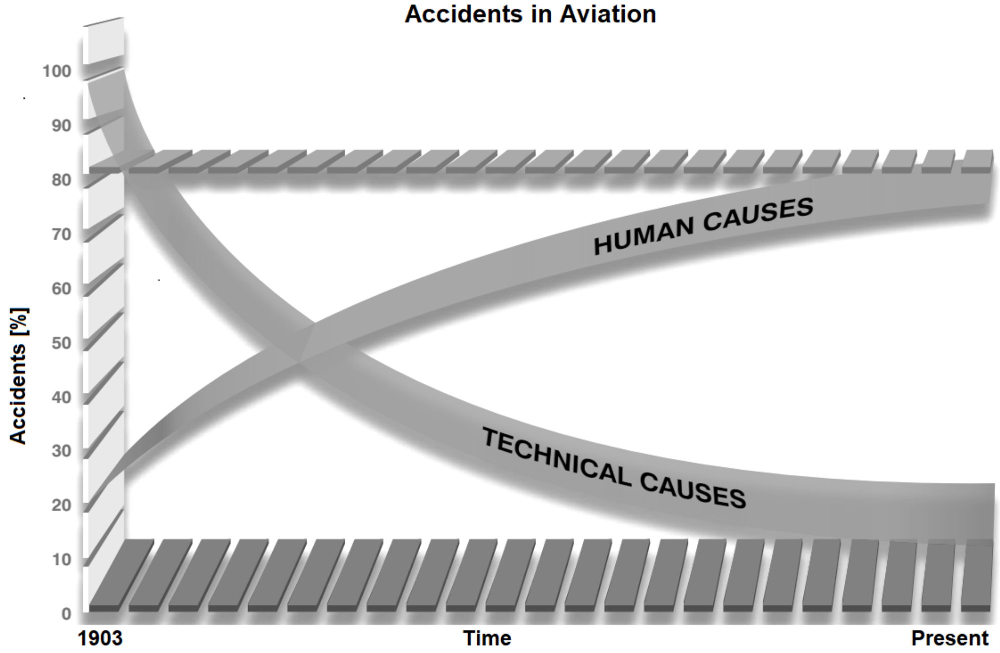


Figure 4.6: Root causes trend of aviation accidents (adapted from (Federal Aviation Administration n.d., p. 28))

While in the past, major accidents were often related to technical causes, this has changed with time (see Figure 4.6). Roughly 80 percent of all aviation accidents can nowadays be related to human errors. For this reason, great efforts have been made to model human factors and make reliability as well as risk assessment quantifiable.

The probability of human error can be estimated by relevant performance shaping factors such as training, stress or complexity of task. Over the years a large amount of data has been collected, especially within the rail sector, which enables the evaluation of human error probability. (Smith 2011, p. 140-141) The HRATs aim to prevent unfavorable results such as poor system performance or low safety (Cassis 2018, p. 14).

One early developed method is the Human Error Assessment and Reduction Technique (HEART) by J.C. Williams in 1988 (Williams 1988). This method serves the assessment of human reliability and the identification of major influences on human error as well as human performance. Due to its straightforward, simple, and relative quick application, it is applicable to any industry that aims to evaluate human reliability. (Smith 2011, p.142; Bell & Williams 2017, p. 3-4) Therefore, HEART is used within the IM model to assess the impact of human factors on the performance.

For the application of HEART, there are nine generic task types with basic failure probabilities given. These can be found under the term Nominal Human Unreliability (NHU) in Appendix A.1. There are also thirty-eight Error Producing Conditions (EPC) with two recently added EPCs. EPC is also known within HRAT as performance shaping factor which represents the effect of human factors on the failure probabilities. (Bell & Williams 2017, p. 3-4) Each EPC is given with a maximum multiplier which expresses the maximum impact of the human factor on the reliability. This maximum multiplier can be adjusted by the Proportion of Effect (PE) in a range from zero to one, in order to represent the intensity of effect. The extremes $PE = 1$ and $PE = 0$ represent the maximum and minimum intensity of the effect, respectively. Generally, the PE is assessed or suggested for every EPC by an expert or the applicant of the method. (Smith 2011, p.142 Cassis 2018, p. 14) The Assessed Impact (AI) of each EPC can be calculated as follows:

$$AI = ((EPC - 1) \cdot PE) + 1 \tag{4.5}$$

Subsequently, the Human Error Probability (HEP) of one specific maintenance task can be assessed as follows:

$$HEP = NHU \cdot \prod_{i=1}^{k} AI_i \tag{4.6}$$

In short, the application of HEART can easily be managed with the following steps:

1. Select one of nine generic task types and the associated NHU which can be found in Appendix A.1.
2. Select all EPCs which affect the human error reliability and assess an appropriate PE for each EPC to describe it's intensity.
3. Use Equation 4.5 to calculate AI for each EPC with predefined PE and maximum multiplier retrieved from Appendix A.2.
4. Use calculated AIs of previous step and Equation 4.6 to assess the task's human error probability.

4.4 Imperfect Maintenance Module for the Simulation Framework

In the following subsection the introduced methods above will be combined to establish the IM model. For this, the HEART method is implemented, predefined parameters are explained and boundaries are set. Finally, the calculated human unreliability is combined with the IM methods: adapted normal distribution for the pressure check and modified effective age method for pressure restoration. The second subsection provides a description of the imperfect maintenance simulation framework.

4.4.1 Establishment of the Imperfect Maintenance Model

For the implementation of HEART, each maintenance task will be assigned to one of nine generic task types of Appendix A.1. In addition, each presented parameter in Figure 4.5 will be assigned to an appropriate EPC from Appendix A.2. For each EPC, the respective PE has to be developed. For this, additional human performance studies will be considered to define the intensity of each EPC with respect to the chosen parameter value.

Both tasks, tire pressure restoration as well as detailed inspection plus tire pressure restoration, will be assumed as the same task type with the same NHU. Additionally, one generic task type has to be selected for the tire pressure check. Both task types are depicted in Table 4.1. Note, that the replacement of the tire will be neglected as it is assumed to be a perfect repair.

Table 4.1: Nominal human unreliability for each task (Cassis 2018, p. 39-40)

Tire Maintenance Task	**HEART-Task**		
	Type	Description	NHU
Pressure Check	E	Routine, highly-practiced, rapid task involving relatively low level of skill.	0.02
Tire Restoration	F	Restore or shift a system to original or new state following procedures, with some checking.	0.003

Table 4.1 shows the necessary tire maintenance tasks and the NHUs which will be used for the human reliability analysis. In the following, the parameters and the assumptions under which they are considered for the IM model will be clarified. For the implementation of the IM model the following design parameters are considered:

- Age: Current age of the mechanic.
- Training Level: Number of practical as well as formal training sessions completed.
- Certification level: Number of certification given by type ratings in case of B1, B2 and C holders and by the number of tasks specified on the task list in case of a CAT A holder.

- Experience: Years of experience in the task related position.
- Procedure design: Qualitative assessment of the document to be used.
- Environmental condition: Consideration of different environmental conditions with regard to weather (heat, cold, and humidity), working place and lighting conditions.
- Time-of-day: Time when task is conducted (only assuming start time of task and neglecting task duration).

First, the respective maximum multiplier and therefore the EPC for each parameter has to be selected from Appendix A.2. In Table 4.2 the parameters of the IM model are assigned to a suitable EPC to retrieve the maximum multiplier.

Table 4.2: Overview maximum multiplier of each parameter (Cassis 2018, p. 41-43; Bell & Williams 2017, p. 6-7)

Heart EPCs				
HF Category	Parameter	Type	Description	Multiplier
Knowledge, skills and experience	Training	15	Operator inexperience (e.g. a newly-qualified tradesman, but not an expert)	3
	Experience	15	Operator inexperience (e.g. a newly-qualified tradesman, but not an expert)	3
	Age	38	Age (25-85) of personnel performing perceptual tasks (for each 10 years)	1.16
	Certification	20	Mismatch between education-achievement level of individual & requirements of task	2
Paperwork, manuals & procedures	Procedure design	16	An impoverished quality of information conveyed by procedures & person-person interaction	3
Work environment	Environmental condition	33	A poor or hostile environment	1.15
Fatigue	Time-of-day	39	Variation between diurnal high & low of performance	2.4

The given maximum multipliers are divided into discrete steps by multiplying them with the PEs. Starting with the parameter *age*, for which the HEART method itself has determined that with every ten years between the age of 25 and 85, the maximum multiplier has to be factorized respectively. This means, that the multiplier 1.16 has to be applied for 25 to 34 years old mechanics, 1.16^2 for an age of 35 to 44, 1.16^3 for an age of 45 to 54, and so on. Despite the positive impact of higher experience, with increasing age, according to HEART advancing age is only linked to a constant reduction in reliability in regard to basic cognitive functions. (Bill et al. 2019, p. 7)

Next, the PEs of the parameters *training level*, *certification* and *experience level* are defined. For that, a Korean human capital investment study is utilized (Seong-O Bae et al. 2013). The study evaluates and analyzes employee performance in regard to school education, job training, job experience, language ability and certifications. Within the study, 5,842 employees from the examined company have been evaluated with regard to their performance using a simple score system: A, B, C+, C and D are equivalent to five points, four points, three points, two points and one point, respectively (Seong-O Bae et al. 2013, p. 61-62). The average performance assessment for different levels of training, experience and certification will be used to proportionate the maximum multiplier of each EPC. Study results and PEs are summarized in Table 4.3.

Table 4.3: Overview of PEs for each parameter level experience, training and certification (Seong-O Bae et al. 2013, p. 65)

	Parameter level	Mean Performance	PE	N
Training level	1 (1-5)	3.23	1.00	993
	2 (6-10)	3.42	0.41	2835
	3 (11-15)	3.47	0.25	1568
	4 (16-20)	3.51	0.13	424
	5 (more than 20 training sessions)	3.55	0.00	22
Experience level	1 (5 years or less)	3.23	1.00	1633
	2 (5-10 years)	3.42	0.54	2608
	3 (11-15 years)	3.55	0.22	1131
	4 (16-20 years)	3.64	0.00	425
	5 (20 years or more)	3.54	0.24	45
Certification	0	3.39	0.57	1323
	1	3.43	0.00	1685
	2	3.42	0.14	1046
	3	3.41	0.29	819
	4	3.41	0.29	596
	5	3.36	1.00	245
	6	3.36	1.00	85

For each mean performance, the respective employees sampling frame N, which is the number of employees fulfilling the parameter specification, is given. The best and worst performance values are assigned to a PE of zero and to a PE of one for each parameter constellation. The values in between are interpolated according to:

$$Y_n = Y_1 + \frac{Y_2 - Y_1}{X_2 - X_1} \cdot (X_n - X_1) \tag{4.7}$$

where Y takes values of PE and X takes values of the mean performance. The certification assessment has been limited to six core certificates due to a low number of certification holders with more than six certificates in this study.

The parameter *procedure design* is proportioned into three possible scenarios in order to create equidistant PEs. (see Table 4.4)

Table 4.4: PEs and description of the parameter procedure design

Procedure design	Description	PE
Individual	An individual designed procedure is a procedure that has been individually optimized for the operator. This assumes a procedure form especially designed from the mechanic with the help of a qualified engineer.	0
Standard	The standard designed procedure has been provided by the aircraft manufacturer without any modifications done by the company.	0.5
Poor	A poorly designed procedure is a procedure which has been modified or expanded by a prior mechanic and passed to a new mechanic to follow the next task steps.	1

The IM model distinguishes between an individual, standard, and poorly designed procedure. The procedure has to be classified as one of the three scenarios to define the PE. The scenarios have been assumed to define a best, worst, and mean PE value.

For the parameter *environmental condition*, the PEs are evaluated on the basis of six different environmental conditions in ascending order from worst to best working environment (see Table 4.5). Accordingly, the best working condition is assumed as working inside a facility at bright light. It is assumed that the facility is air conditioned on hot days and heated on cold days, which allows to neglect case distinctions regarding the weather when working inside a facility. The worst working environment is assumed to be working outside under uncomfortable weather and at faint light conditions. In addition, it was assumed that better visibility is more important than adverse weather conditions. With these assumptions, the PEs have been derived in Table 4.5.

Table 4.5: Overview of PEs for the parameter poor environment

Clarifications of different environmental condition	PE
Outside, faint light, uncomfortable weather (OFUW)	1.00
Outside, faint light, comfortable weather (OFCW)	0.80
Outside, bright light, uncomfortable weather (OBUW)	0.60
Outside, bright light, comfortable weather (OBCW)	0.40
Inside, faint light (IF)	0.20
Inside, bright light (IB)	0.00

Since the best case can be assumed with a PE of zero and the worst case is equivalent to one, the remaining environmental conditions have been divided into five equidistant fractions. In the following, the environmental factors working place, lighting and weather are described in more detail. Beginning with the distinction between being inside or outside of a facility, the conditions can be described as followed:

1. Outside refers to line maintenance work on aprons or ramps
2. Inside refers to shop or base maintenance which is considered to be performed within a facility

For the IM model, working outside is assumed to be connected to higher noise levels and a busier working environment than working inside a hangar or within a shop.

Next the definition of comfortable or uncomfortable weather is defined by the "comfort zone" of humidity and ambient temperature (see Figure 4.7).

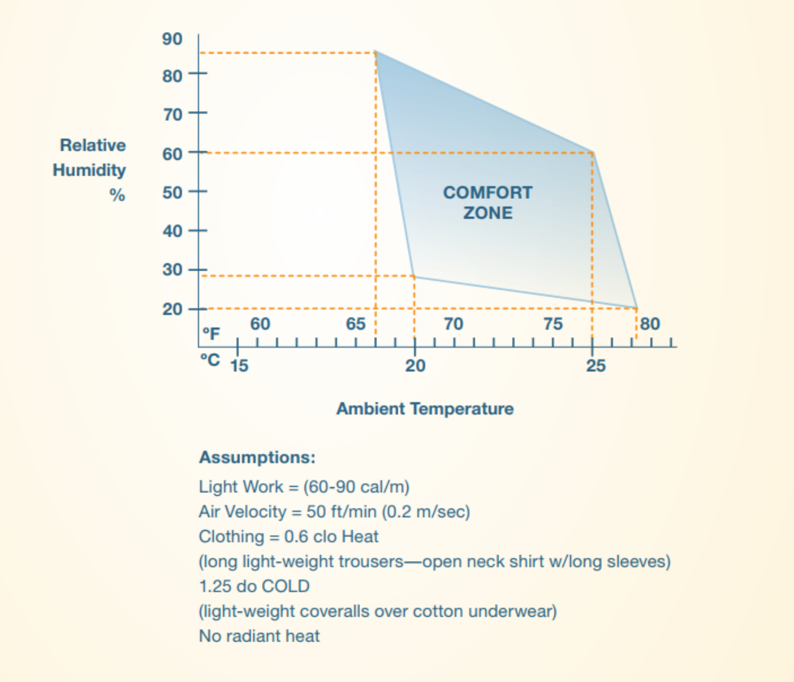


Figure 4.7: Thermal Comfort zone (Maddox n.d., p. 47)

Humans have a narrow "zone" of relative humidity and temperature in which they work comfortable. Within this zone, it is assumed that a high output level can be achieved while outside this "zone" a reduced working level is expected. Accordingly, comfortable weather will be assumed in the IM model with an ambient temperature between 20 to 25 degrees Celsius and a relative humidity between 29 percent to 60 percent. Outside this zone, the human will be considered working under uncomfortable weather conditions.

The factor lighting is considered by facility lighting, natural lighting, and task lighting. While facility lighting is provided by a common lighting system in the facility, including fixtures, and windows, natural lighting is represented by day light. Task lighting includes drop lights, interior aircraft lights, flash-lights, and portable light stands. Task lighting is especially required when working inside the aircraft, in poorly lit areas or during night shifts. If additional task lighting is required to conduct the task, it will be assumed as faint lighting condition.

Finally, the parameter *time-of-day* is proportionate to the effect of fatigue on performance. For this parameter, the human's alertness level is used as an indicator to illustrate his performance. In Figure 4.8, the alertness level of a human is depicted with respect to the time of day.

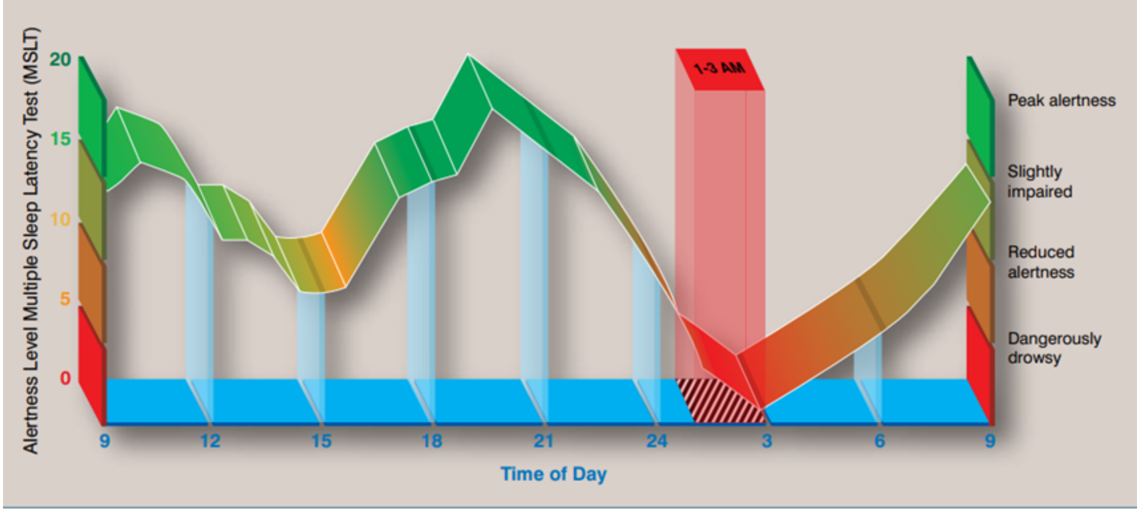


Figure 4.8: Alertness level in respect to time of day (Federal Aviation Administration n.d., p. 18)

According to Figure 4.8, the best performance will be assumed as peak alertness, good performance as slightly impaired, bad performance as reduced alertness, and the worst performance as dangerously drowsy. In Table 4.6, the average alertness level for given time steps have been taken from Figure 4.8. Each average alertness level has been assigned to one of the four human alertness types. With given alertness type and retrieved multiplier the proportion of effects are derived.

Table 4.6: PEs of each parameter step *time-of-day*

From	To	Average alertness level	Human's alertness type	Multiplier	PE
0	3	2.50	Dangerously drowsy	2.4	1.00
3	6	3.50	Dangerously drowsy	2.4	1.00
6	9	7.50	Reduced alertness	1.85	0.77
9	12	15.50	Peak alertness	0	0.00
12	15	12.50	Slightly impaired	1.3	0.54
15	18	14.00	Slightly impaired	1.3	0.54
18	21	17.50	Peak alertness	0	0.00
21	0	13.00	Slightly impaired	1.3	0.54

The HEART method proposes, that the lowest performance, i.e. the lowest reliability, is around 3am. This is assumed to have a maximum multiplier of 2.4 and represent a state of dangerously drowsy alertness. According to Bell et al., at around 14:00 to 15:00, a human unreliability factor of 1.3 can be assumed. This coincides with slightly impaired alertness (Bell & Williams 2017, p. 7). Peak alertness is assumed with a multiplier of zero. The reduced alertness multiplier is the mean between the multipliers of dangerously drowsy and slightly impaired alertness. For all time units belonging to the same human alertness type the previously described multipliers have been assigned. The best and worst alertness levels are assigned to a PE of zero and one. The remaining PEs are proportioned to the multipliers.

With given HEART EPCs, PEs as well as NHU, the human error probability can be calculated. Within the IM model, this probability will be used to define the performance of a mechanic. It is assumed that the human reliability to conduct a specific task is equal to the performance efficiency.

$$HP = HR = 1 - HEP \tag{4.8}$$

where Human Performance (HP) describes the percentage of performance efficiency like demonstrated in Equation 4.8, HR refers to human reliability and HEP refers to human error probability from Equation 4.6. For the pressure restoration task HP is used within the effective age model as the parameter restoration level A_n (see Equation 4.2), with the assumption $A_n = HP$. For the tire pressure check the HEP parameter is used to determine the interval pressure boundaries a_x and b_x for the normal distribution. (see Subsection 4.1.2) These are calculated as followed:

$$a_x = p_{real} - \frac{HEP \cdot p_{real}}{2} \tag{4.9}$$

$$b_x = p_{real} + \frac{HEP \cdot p_{real}}{2} \tag{4.10}$$

4.4.2 Code Description

The imperfect maintenance module can expand the DLR's existing simulation framework by the additional capability to run the simulation under the assumption of imperfect maintenance. For this, the existing simulation framework has to be modified first to allow simple attachments of further modules. This modification is not possible within the scope of this work due to time constraints. Therefore, it was decided to use an abbreviated version of the simulation framework to demonstrate the functionalities of the imperfect maintenance module. For this, two python files have been created. The first python file is the main script which runs necessary functions of the existing simulation framework. Within this file, input data, data bases, and settings are read in from external data sources (e.g. init-file, excel, etc.) or defined internally as variables. The second python file contains the class "Imperfect Maintenance". Within the class, user input and data bases related to the IM are processed for the execution of necessary functions. Methods (functions) and attributes have been developed within the class file to calculate the system's virtual condition after an imperfect repair. Moreover, within the main script an instance of the IM class is created and functions are triggered for the IM run. In Figure 4.9 the explained simulation sequence is depicted.

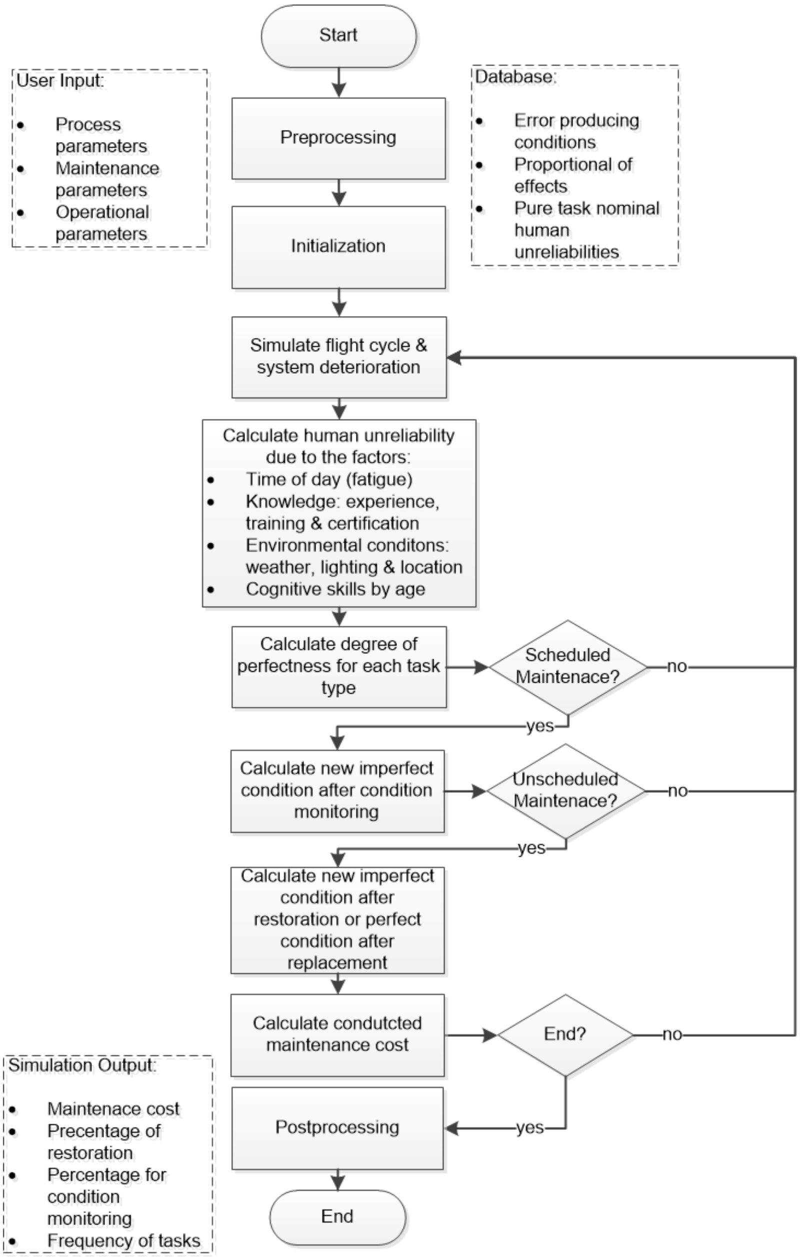


Figure 4.9: IM Module integrated in simulation framework

The simplified simulation sequence depicts the relevant functions and information necessary for the calculation of imperfect maintenance. User input and data bases relevant to the IM are depicted. The parameters time-of-day, experience level, training level, number of certification, environmental condition, and age of the mechanic have to be set within the user input init-file. The database contains all relevant information of the previously explained methods in order to calculate the system condition. The respective parameter values and boundaries of the user input parameters as well as the data base parameters are explained in Subsection 4.4.1.

By running the main file, first all available data will be read in and saved (see Figure 4.9 Preprocessing). Next, the initialization of the parameters and objects follows. The data is then used in the continuous simulation of flights and system deterioration to determine the virtual state of the system under the assumption of IM. After each discretely simulated maintenance task, the tire pressure condition is determined under the assumption of IM. The loop continuously simulates flights and maintenance task executions. This loop terminates when reaching the simulation time span, e.g. a certain number of FC. In the final stage, the operator receives an excel file that contains the IM simulation outputs, which are the percentage of human reliability for the tasks pressure restoration and condition monitoring, the frequency of conducted task types during the run and the overall maintenance cost.

5 Sensitivity Analysis and Results

In this chapter, a sensitivity analysis is conducted to assess the impact of the developed IM module's parameters on a defined objective. The sensitivity analysis is performed with a parameter study, in which the module's inputs are examined on various output parameters. The conducted parameter study and the gathered results are presented in Section 5.1. Moreover, the sensitivity analysis results are examined to derive maintenance strategies for the TPIS under the assumption of imperfect maintenance. The derived maintenance strategies are presented in Section 5.2 and their cost saving potentials are compared and discussed in Section 5.3.

The parameter study is conducted with the abbreviated version of the simulation framework described in subsection 4.4.2. The existing framework functionalities allow the evaluation of condition monitoring systems such as the TPIS by calculating the overall maintenance cost within the process. The abbreviated simulation framework exclusively includes the cost which results from discretely conducted maintenance task during the simulation time span. They are presented in Table 5.1.

Table 5.1: Maintenance cost parameters (Meissner et al. 2020, p. 8)

Parameter	Parameter description	Value	Unit
c_{func}	Cost functional check	10	$
c_{rest}	Cost restoration	50	$
c_{insp}	Cost inspection	100	$
c_{repl}	Cost replacement	1,000	$

Note that the c_{func} is only considered for the manual inspection method, since the automated method does not require a mechanic to read the pressure from the tire. Furthermore, TPIS acquisition costs is neglected in the cost calculations.

Maintenance cost is a common objective when comparing imperfect repair to perfect repair (Wang & Pham 2006, p. 10). Therefore, maintenance costs will be used as the objective factor for the sensitivity analysis.

Due to the probabilistic nature of the IM model (see subsection 4.1.2), each solution is generated 50 times and the mean values are used to yield comparable results. A reference configuration (RC) for the sensitivity analysis is established in order to conduct the parameter study. For each parameter variation, the reference configuration will be fixed and one specific parameter is changed stepwise to assess its impact on maintenance cost.

The parameters of interest and their values which are considered for the parameter variations are depicted in Table 5.2.

Table 5.2: Parameter steps for parameter study

Parameter	**Parameter description**	**Parameter steps**
t_{day}	Time-of-day	[03:00; 06:00; 09:00; 12:00; 15:00; 18:00; 21:00; 00:00]
age	Age	[25; 35; 45; 55; 65]
EL	Experience Level	[1; 2; 3; 4; 5]
TL	Training Level	[1; 2; 3; 4; 5]
NC	Number Certifications	[0; 1; 2; 3; 4; 5; 6]
EC	Environmental Condition	[OBUW; OFUW; OFCW; OBUW; OBCW; IF; IB]
PD	Procedure Design	[Poor (P); Standard (S); Individual (I)]
RD	Restoration Degree	[Perfect (P); Imperfect (IP)]
IPM	Inspection Method	[Manual (M); Automatic (A)]
II	Inspection Interval	[1; 6; 18]

The parameters and their established values are defined and explained in subsection 4.4.1. The chosen parameter inputs of the RC as a representation of one operational scenario for the tire pressure maintenance task can be seen in Table 5.3. Note that the adjustment of the respective parameters to each other has been neglected, as the RC only serves as a fixed comparison scenario for the parameter study.

Table 5.3: Reference configuration for the parameter study

Parameter	Parameter description	Value
age	Age	48
t_{day}	Time-of-day	05:00am (shift start)
EL	Experience Level	2
TL	Training Level	4
NC	Number Certifications	2
EC	Environmental Condition	OFCW
PD	Procedure Design	standard
IPM	Inspection Method	manual
II	Inspection Interval	18
m	Simulation time span	1000

In the following, the reason for each selected value is explained. For the RC, the age of a mechanic has been set to 48, which represents the average age of an aircraft mechanic as stated by the U.S. Labor Force Statistic in the year 2019 (U.S. Burau of labor statistics 2020). It has been assumed that the mechanic checks the tire pressure at 5 am. The parameters experience level, training level, and number of certifications in the RC are taken from the Korean investment study containing an average value of each parameter (see subsection 4.4.1). On average, the employees have 9.63 years of working experience, completed 19.2 training sessions, and possesses 2,36 certificates which are respectively equivalent to a level two experience, level four training, and two certificates (Seong-O Bae et al. 2013, p. 63). The environmental condition is assumed as working outside, with faint light conditions, and under comfortable weather (OFCW). Since the manual inspection method is state-of-the-art for tire pressure checks and every third day an inspection is performed, the manual method and 18 FC (assuming six FC per day) for the inspection interval are defined within the RC. With an increasing simulation time span, a better comprehension of the IM module's characteristics can be achieved due to clearer differences between the calculated maintenance cost. This allows a better recommendation regarding the choice of an optimal maintenance strategy. Hence, the sensitivity analysis of each parameter set is calculated for the simulation time span of 1,000 FC. For more details with regard to the individual parameters refer to subsection 4.4.1.

5.1 Parameter Study

The sensitivity analysis is conducted via parameter variation with regard to the chosen objective maintenance cost. Additional outputs of the simulation runs are frequency of maintenance tasks, Performance Condition Monitoring (PCM), and Performance Restoration (PR). The latter two parameters describe the performance efficiency of a mechanic and have an impact on the tire pressure condition (see Subsection 4.4.1). These parameters are calculated as HP in Equation 4.8 applying the HEART method described in Section 4.3. The additional parameters serve the examination of the calculated maintenance costs and the evaluation of the IM module.

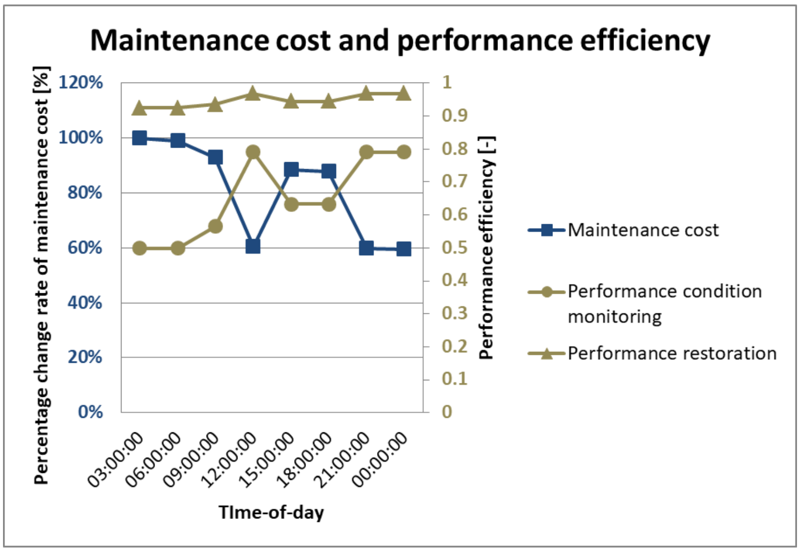
Within the abbreviated simulation framework, the tire pressure is checked at given inspection intervals. Based on the given pressure value, there are various maintenance tasks which can be performed. In Figure 2.4, the tire pressure threshold values and the resulting maintenance tasks are shown. The frequency of the conducted maintenance tasks is derived by recording the number and type of maintenance tasks performed during the simulation time span. Depending on the task performed, the specific maintenance cost is recorded as well. The individual costs are given in Table 5.1.

For each parameter variation, two graphs are depicted. The first graph visualizes the maintenance cost, PCM, and PR trends when varying a specific parameter. The maintenance costs are normalized with regard to the first variable value in order to indicate a percentage change of the costs, i.e. the objective, in relation to the defined parameter value.

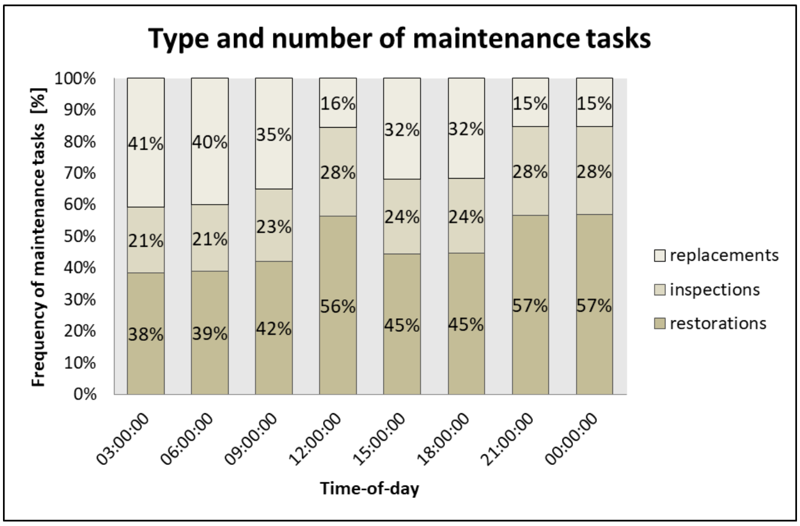
The second graph illustrates the frequency of the conducted maintenance tasks during the simulation time span. For this, the frequency of the maintenance tasks are depicted as fractions of the total maintenance tasks performed. The varying frequency of restorations, detailed inspections and replacements are decisive for the analysis of the varying maintenance costs and are therefore depicted.

5.1.1 Time-of-day

The parameter time-of-day depicts the alertness level of a mechanic and hence, his maximum ability to perform a task as accurately as possible. Depending on the time of day, the mechanic's performance accuracy varies. In Figure 5.1, the results of the parameter variation for time-of-day are depicted.



(a) Results of cost, PCD, and PR



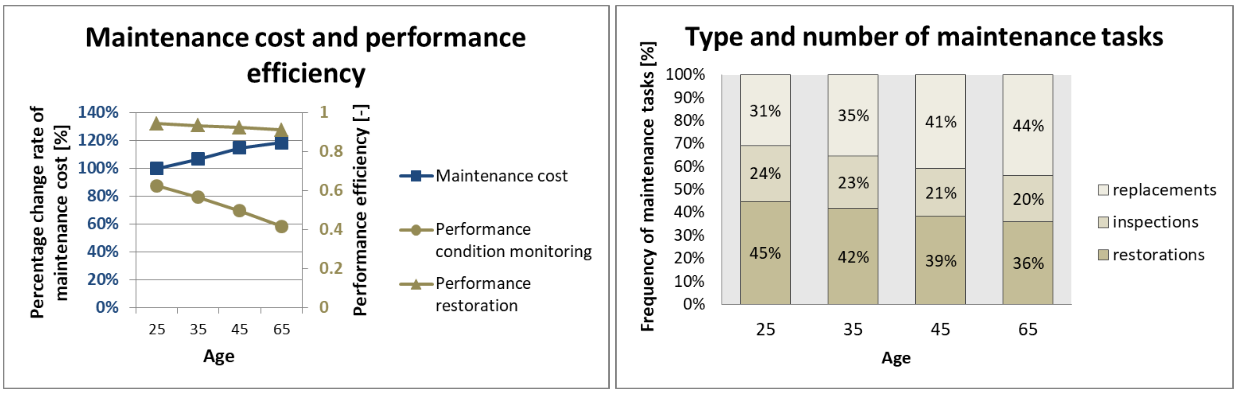
(b) Results maintenance task frequency

Figure 5.1: Results of the parameter variation time-of-day

The parameter time-of-day shows a significant impact on the maintenance cost. A deviation of about 40 percent cost decrease compared to the initial cost value can be seen in Figure 5.1a within the time interval of 3:00 to 12:00. The lowest maintenance cost is given at noon as well as between 21:00 and midnight, which also indicates the highest PCM and PR values. Clearly, a decline in performance efficiency also seems to lead to an increase in maintenance cost (see 12:00 to 15:00 in Figure 5.1a). High maintenance cost can be associated with a higher fraction of conducted tire replacements (see Figure 5.1b). Low maintenance cost on the other hand can be associated with a higher frequency of restorations. These values indicate that poorer performance leads mainly to costly tire inspections or replacements. An early or in this case a more precise execution of a task leads to an early recognition of what the tire needs and can thus prevent costly inspections or tire replacements. The large difference between PCM and PR values can be explained by the NHUs selected (see Subsection 4.4.1) and applied to assess the HEP in Equation 4.6. Therefore, the PR varies much less compared to the PCM.

5.1.2 Age

The age parameter represents the cognitive abilities that a mechanic possesses with advancing age. With increasing age, a deterioration of cognitive abilities and thus a decline in performance is assumed. This implemented dependency leads to the results shown in Figure 5.2.



(a) Results of cost, PCM, and PR

(b) Results maintenance task frequency

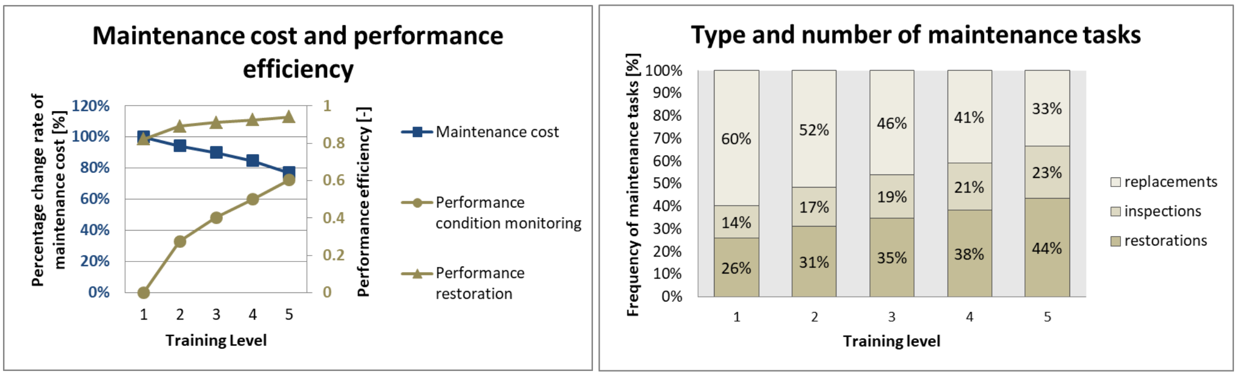
Figure 5.2: Results of the parameter variation age

By assuming a lower performance capability with increasing age, an increase in maintenance costs can be observed. From the age 25 to 65, the percentage cost rate increases by 20 percent compared to the initial cost. In Figure 5.2a, a steeper slope can be seen for PCM than for PR. PR remains almost constant with the age. Hence, cost changes can be attributed mainly to PCM. The lowest PCM value contributes to the highest number of replacements (see Figure 5.2b). With a low PCM value, the IM module calculates a pressure value that deviates significantly from the real pressure value. This incorrect pressure value seems to lead to decisions of subsequent maintenance tasks that have a negative effect on maintenance cost. A possible explanation for this is, that tires are replaced although it is not necessary, or that further inspections are carried out although restoration work should be sufficient.

5.1.3 Training Level

Five discrete training levels have been defined for the IM module. Each training level represents a specific number of training courses completed (see Table 4.3).

The effects of changing this parameter are shown in the following figures.



(a) Results of cost, PCM, and PR

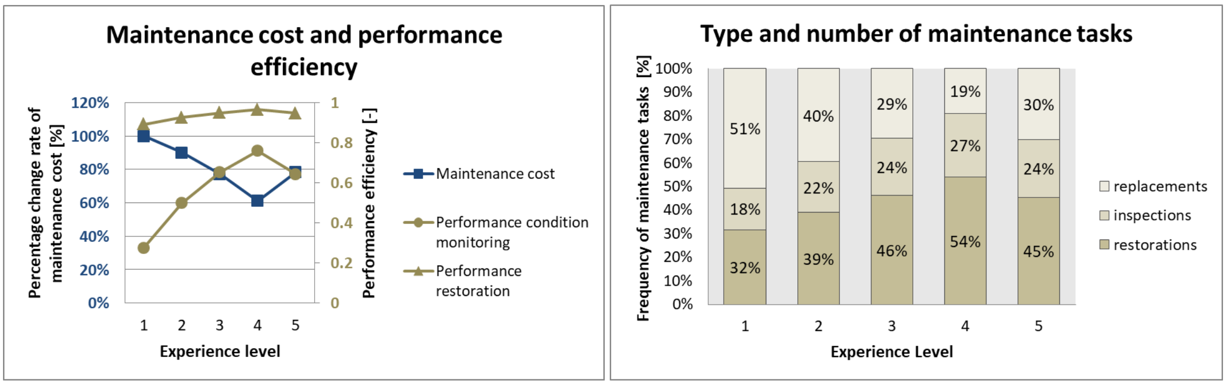
(b) Results maintenance task frequency

Figure 5.3: Results of the parameter variation training level

Training level is the only parameter within the parameter study for which a performance efficiency of zero percent is achieved when being varied (see Figure 5.3a). The existing negative impact of the RC on performance partly contributes to this solution. However, a strong influence of the training level on performance and thus on maintenance cost can be identified. The slope of the PCM trend indicates a significant impact on maintenance cost. Between the lowest training level and the highest one a decrease of 20 percent in maintenance cost can be observed (see Figure 5.3a). The lowest maintenance cost is achieved by the highest level of training. For this parameter, the maintenance cost decreases with increasing numbers of restorations and decreasing number of replacements (see Figure 5.3b).

5.1.4 Experience Level

The parameter experience level, similar to training level, is defined by five discrete levels that have been defined for the IM module. Each level represents specific years of experience the mechanic has collected in this position (see Table 4.3). The following graphics illustrate the results of the parameter variation.



(a) Results of cost, PCM, and PR

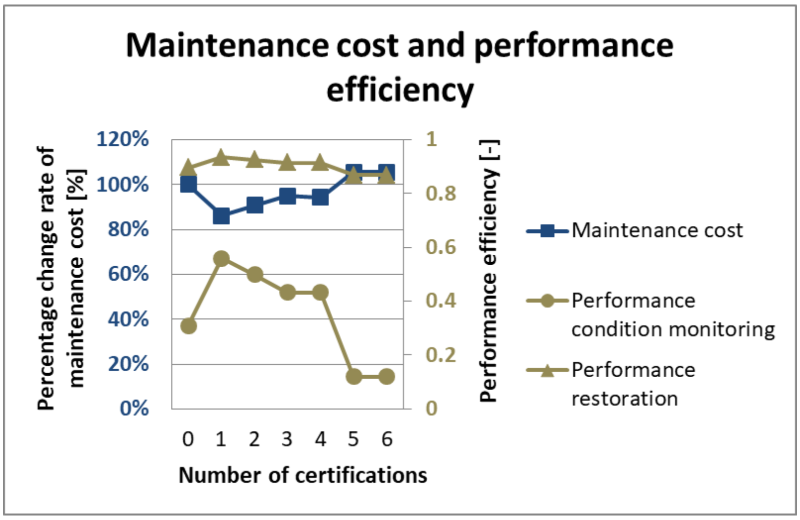
(b) Results maintenance task frequency

Figure 5.4: Results of the parameter variation experience level

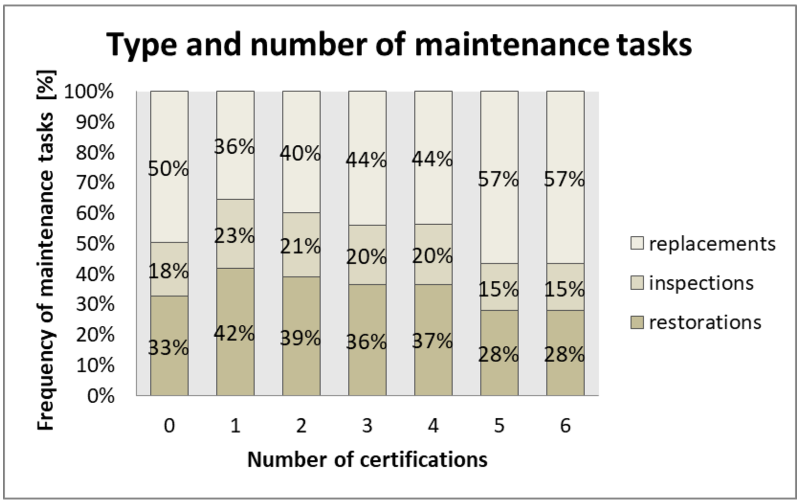
Maintenance cost is reduced up to an experience level of four for which the local optimum is reached. Afterwards, the maintenance cost increases for an experience level of five (see Figure 5.4a). This trend can be explained by the assumptions made for PE's experience level in Table 4.3. From highest value to lowest value a cost deviation of about 40 percent can be observed. The steep slope of maintenance cost as a function of experience indicates a strong impact of this parameter on maintenance cost. Increasing frequency of restorations and inspections as well as decreasing frequency of replacements which can be seen in Figure 5.4b result in a decline in maintenance cost which can be seen in Figure 5.4a.

5.1.5 Number of certifications

This parameter is defined for zero to six possible certificates. The results of the parameter variation are depicted in Figure 5.5.



(a) Results of cost, PCM, and PR



(b) Results maintenance task frequency

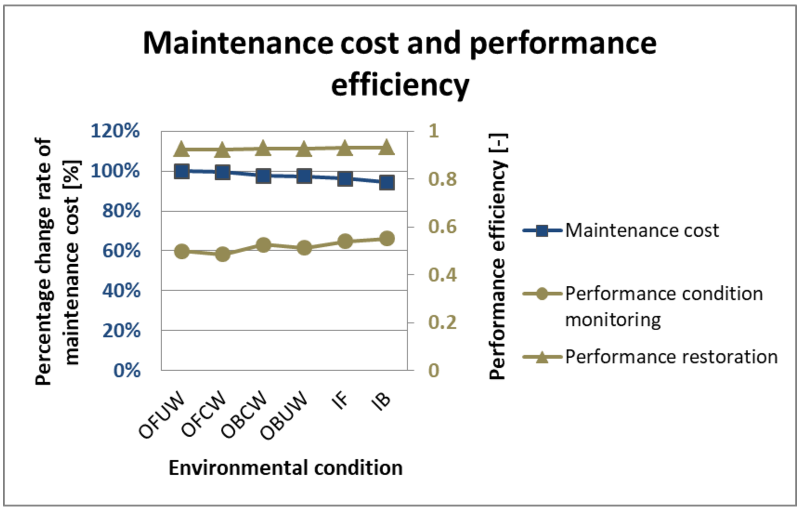
Figure 5.5: Results of the parameter variation number of certifications

The parameter number of certifications shows major fluctuations on the output. Mechanics possessing one certificate have the highest performance efficiency for PCM and PR which implies the lowest maintenance cost for this variation. The highest expenses are reached for mechanics possessing five or six certificates. The best to the worst solution shows a difference in maintenance cost of about 20 percent. Three and four certificates as well as five and six certificates show consistent performances. The slight variations between the costs for these parameter values result from the probabilistic nature of the IM module. Consistence in performance also results in consistent distribution of the maintenance task frequency. The lowest cost is associated with the lowest fraction of replacements but the highest fraction of restorations.

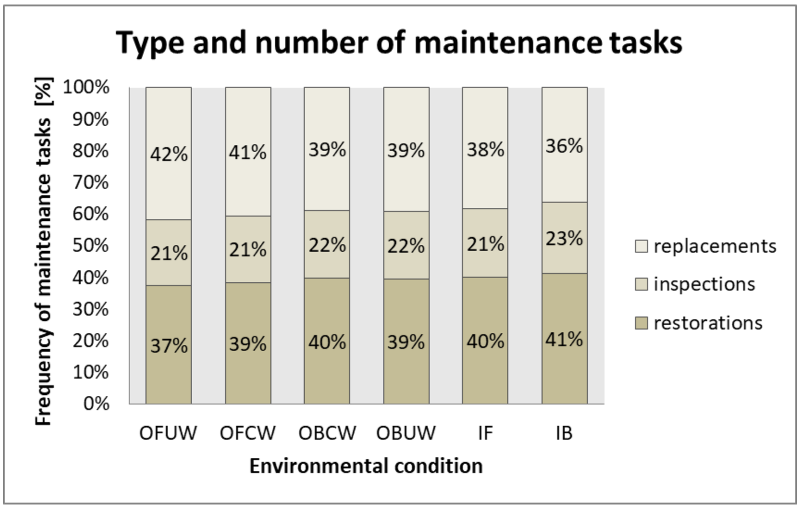
In contrast, the highest cost is given for the highest replacement fraction and lowest restoration fraction (see Figure 5.5b).

5.1.6 Environmental condition

Six different environmental conditions have been defined for the IM module. Each of them represent a different operational environment for the mechanics and influences their ability to perform. The following graphics illustrate the impact of this parameter on the defined objective.



(a) Results of cost, PCM, and PR



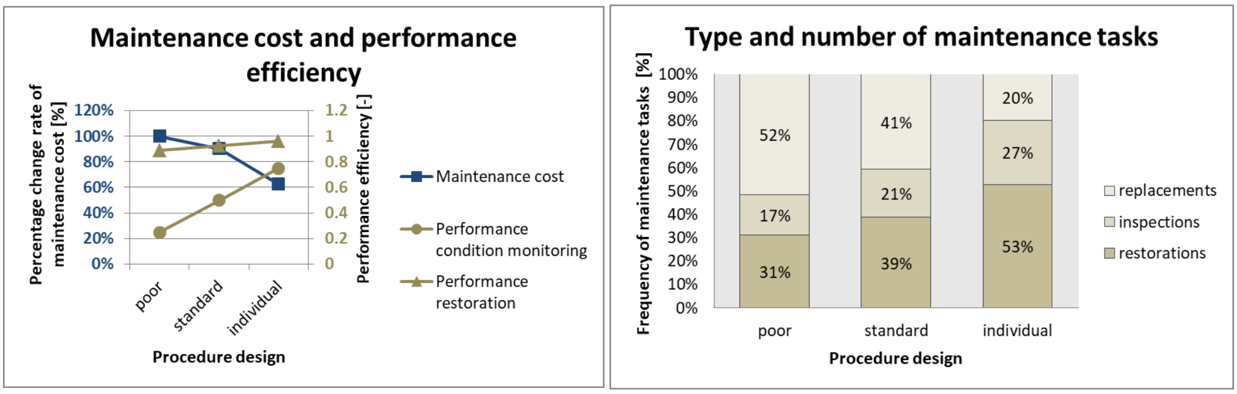
(b) Results maintenance task frequency

Figure 5.6: Results of the parameter variation environmental condition

The parameter environmental condition shows small impact on the maintenance cost. Best to worst solution only show a change about six percent in maintenance cost. In comparison to the previous parameter variations, the curve of PCM changes only slightly. Moreover, maintenance task frequencies show only small changes in their distributions (see Figure 5.6b). Nevertheless, the best solution meaning the lowest cost is given for the environmental condition IB and the worst solution is given for the environmental condition OFUW (see Figure 5.6a).

5.1.7 Procedure Design

Procedure design is divided into poor, standard and individual design. Each design contributes to a different performance accuracy of a maintenance task. The parameter variation is illustrated in Figure 5.7.



(a) Results of cost, PCM, and PR

(b) Results maintenance task frequency

Figure 5.7: Results of the parameter variation procedure design

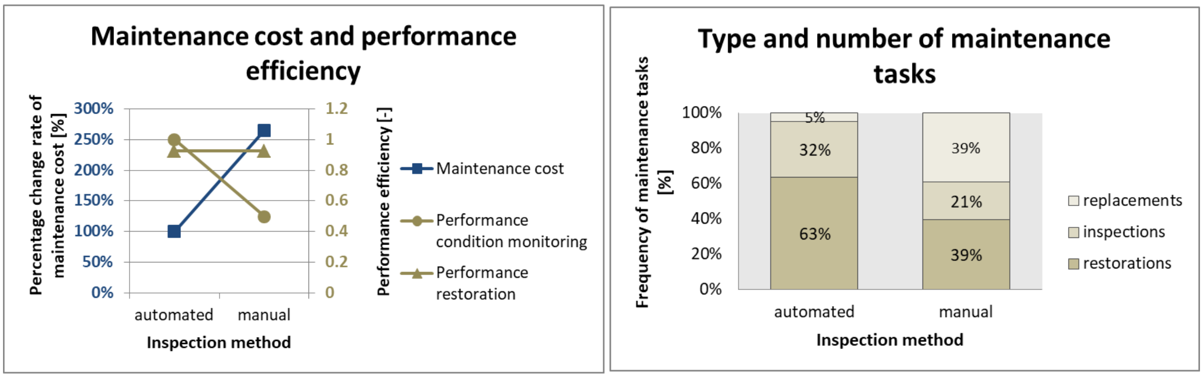
The parameter procedure design has a significant influence on maintenance cost. About 40 percent maintenance cost savings can be achieved between a poorly and an individually designed procedure (see Figure 5.7a). Both, PCM and PR have a positive trend starting at the poorly to the individually designed procedure.

The fraction of replacements falls to only 20 percent when considering the individually designed procedure. In the case of poorly designed procedures, more than half of the conducted maintenance tasks are covered by tire replacements (see Figure 5.7b). Hence, the para-meter procedure design contributes significantly to the distribution of maintenance tasks and maintenance cost.

5.1.8 Inspection Method

For the parameter inspection method, the manual method, which is state of the art, is compared to the automated method represented by the TPIS. The parameter variation is performed for a constant inspection interval, despite the possibility for a higher frequency of data collection using the TPIS. The variation of the inspection interval is presented in the next subsection.

The results of the simulation runs for the parameter inspection method are depicted in Figure 5.8.



(a) Results of cost, PCM, and PR

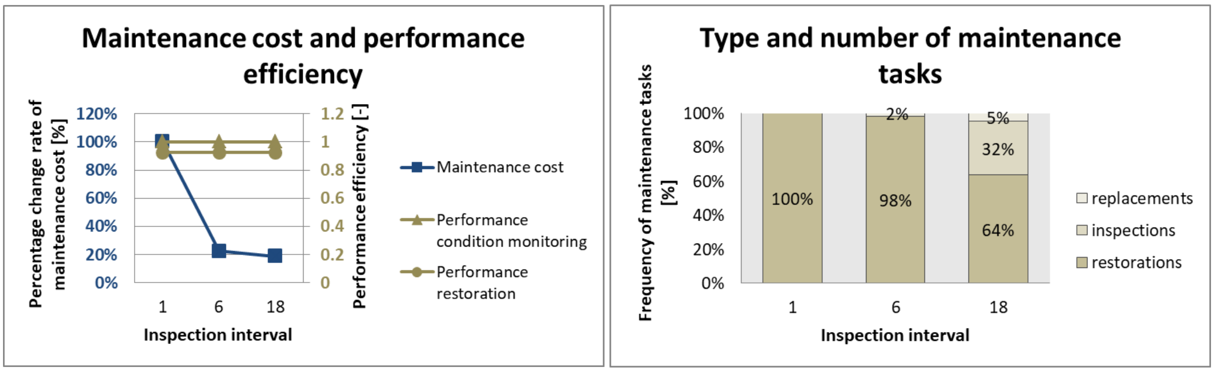
(b) Results maintenance task frequency

Figure 5.8: Results of the parameter variation inspection method

In comparison to the automated method, a duplication of maintenance cost for the manual method can be seen in Figure 5.8a. A higher cost saving potential than with this parameter has only been discovered with the parameter variation of the restoration degree in subsection 5.1.10. It has been assumed that the automated inspection method, i.e. the use of the TPIS, results in a PCM of one which is equivalent to a perfect maintenance. PR of the manual as well as the automated method are identical since the TPIS has no effect on the restoration task. An extreme reduction in replacement frequency is the result when using the TPIS (see Figure 5.8b). This reduction is achieved by a higher frequency of restorations. The manual method also represents the parameter combination of the RC. The RC results in a task frequency distribution of 39 percent replacements, 21 percent inspections and 39 percent restorations.

5.1.9 Inspection Interval

For the parameter inspection interval, the RC is adjusted with regard to the inspection method. As more frequent tire pressure measurements are more likely to be achieved with the TPIS, the automated method will be used for the next parameter study.The inspection interval is viewed for tire pressure checks conducted after each flight cycle, every sixth flight cycle and every 18th flight cycle.



(a) Results of cost, PCM, and PR

(b) Results maintenance task frequency

Figure 5.9: Results of the parameter variation inspection interval

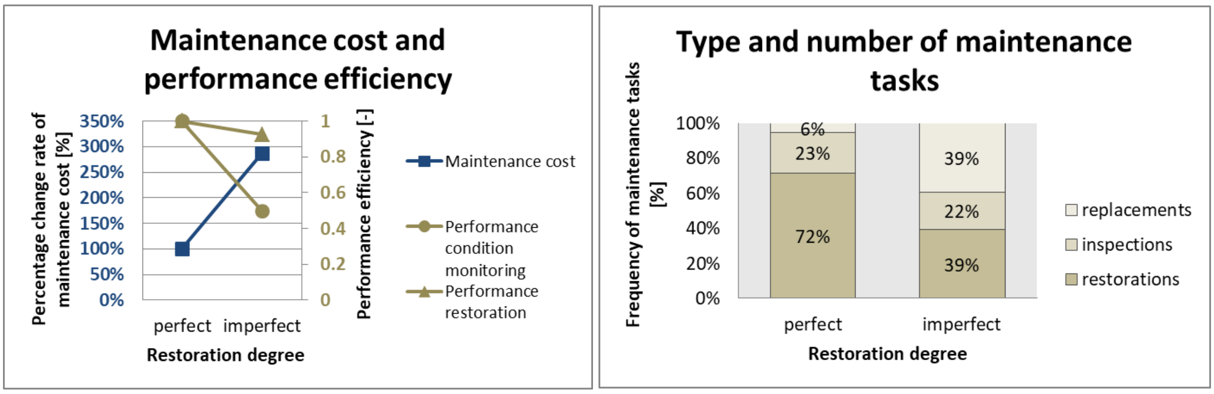
Between the inspection interval of one FC to six FC, there is a significant jump in the maintenance cost rate (see Figure 5.9a). About 80 percent maintenance cost deviation lies between these two parameter values. The potential of maintenance cost savings decreases when comparing the inspection interval of every sixth FC to every 18th FC. The lowest maintenance cost is given for the inspection interval of 18 FC.

The inspection interval has no impact on PCM nor on PR. The inspection interval only contributes to the distributions of conducted maintenance tasks and therefore on the maintenance cost. Unlike parameter variations considered previously, a lower frequency of replacements does not lead to lower maintenance cost in this case. The total amount of maintenance tasks performed varies considerably between the three inspection intervals. Considering the tasks with absolute values, the restoration task in case of one FC interval is conducted six times more frequently than the case of six FC intervals which accordingly leads to a cost reduction of about 1/6. In both cases, the tire pressure never or almost never achieves a pressure value which would result in any heavier tasks such as intensive inspection or replacements. When comparing the six FC interval case to the 18 FC case, it can be observed that both cost approach each other, since higher costs are given for heavier tasks such as inspections and replacements in the interval 18 FC. Hence, the maintenance cost decreases with a flatter slope between both intervals.

Currently this does not seem to be an important parameter for the IM module (impact on PCM or on PR), however it is an important parameter for the development of optimal maintenance strategies.

5.1.10 Restoration Degree

The restoration degrees an item can achieve after maintenance are perfect, minimal, imperfect, worse or worst. These terms have been explained in Section 2.5. Since the IM module is only capable of evaluating the cases imperfect and perfect repair, only these restoration degrees are varied for the parameter variation.



(a) Results of cost, PCM, and PR

(b) Results maintenance task frequency

Figure 5.10: Results of the parameter variation restoration degree

The comparison between perfect and imperfect repair shows, what the existing simulation model is neglecting when considering perfect repair. The imperfect repair shows a triple in maintenance costs when comparing these two cases (Figure 5.10a). Note, that the RC is not the optimal parameter combination, but the most common scenario in reality. Appropriate maintenance strategies are necessary to consider and optimize the impact of imperfect maintenance.

5.2 Derivation of Maintenance Strategies

In this section, the parameters are assigned with a ranking scale in order to illustrate their importance for developing prescriptive maintenance strategies. Each parameter is proportioned between the best and worst solution of the parameter study which illustrates the degree of influence on maintenance cost. The following figure summarizes the results of the parameter study.

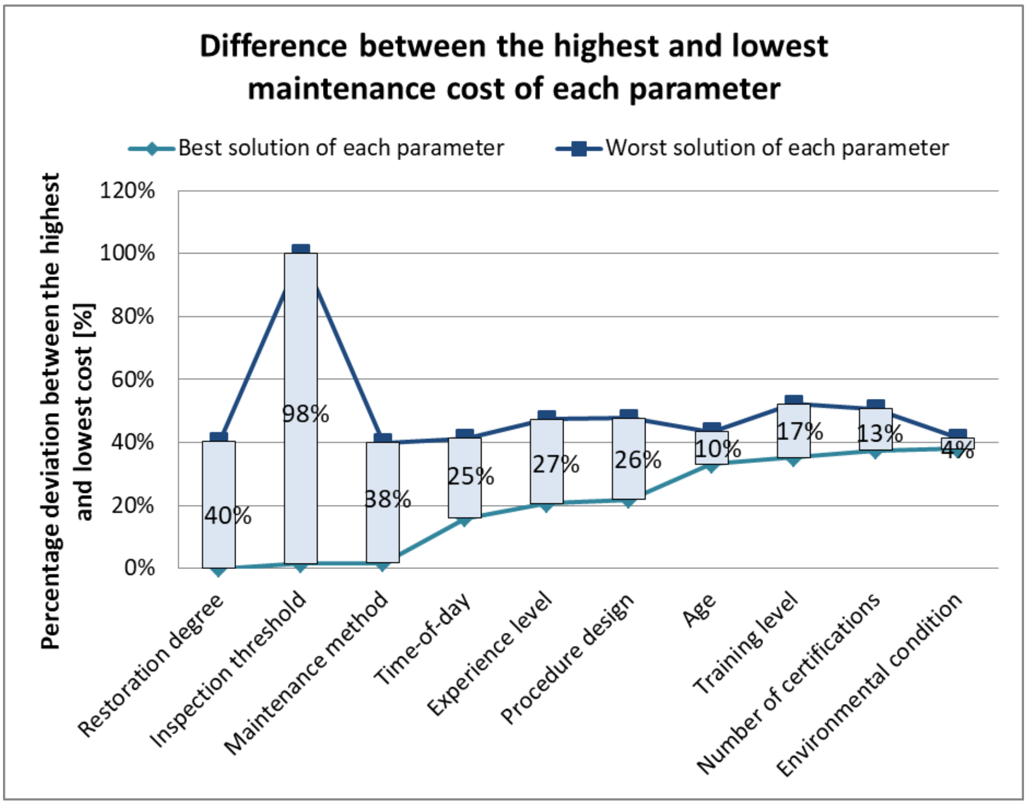


Figure 5.11: Maintenance cost ranking of the parameters

In Figure 5.11, the best and worst solutions, i.e. lowest and highest maintenance cost, gathered from parameter variations are depicted. Each best and worst solution is connected by a deviation bar which illustrates the range of influence on the output. The lowest and highest maintenance cost of all simulation runs are normalized to zero and 100 percent, respectively. All other solutions are interpolated between these two extremes.

The values of the parameters restoration degree, inspection interval and inspection method come closest to the minimum cost achieved in all runs. The highest maintenance cost is achieved by the worst solution of the parameter inspection interval. Moreover, the parameters training level and number of certifications show a significant negative impact on maintenance cost.

The bars that illustrate the difference between the best and worst solution of each parameter variation are utilized to define the importance of each parameter, since these show the potential of maintenance cost savings. Accordingly, broader bars compared to shorter ones have a stronger impact on maintenance cost. In Table 5.4, the parameters are arranged in descending order according to deviation bar length.

Table 5.4: Priority level of the parameters according to their impact on maintenance cost

1.	Inspection interval
2.	Restoration degree
3.	Inspection method
4.	Experience level
5.	Procedure design
6.	Time-of-day
7.	Training level
8.	Number of certifications
9.	Age
10.	Environmental condition

According to Table 5.4, the parameter inspection interval takes the highest priority in terms of influencing maintenance costs. The second highest priority is given to restoration degree which shows the importance of considering imperfect maintenance when developing maintenance strategies. The third highest priority represents the strong impact of using TPIS when considering imperfect maintenance. Below these parameters, a list of the priorities of the IM module's HF parameters is presented.

For favorable maintenance strategies, an optimal inspection interval has to be selected. Moreover, the right degree of restoration has to be chosen, i.e. whether a rough perfect maintenance or a more precise imperfect maintenance has to be considered and which method should be used, the conventional or the automated inspection method. In addition, an optimization in maintenance cost can be achieved with the HF parameters, if imperfect maintenance is the case.

Goal of this work is to derive prescriptive maintenance strategies for the TPIS and compare the solutions with the conventional, state-of-the-art maintenance process. For this purpose, three maintenance strategies, which can be derived from the parameter study, are presented and their potential in maintenance cost savings are discussed in the next section. The state-of-the-art maintenance approach is compared to the:

- Manual maintenance approach with optimized human factors,
- automated (TPIS) maintenance approach, and

- automated (TPIS) maintenance approach with optimized human factors.

The optimization of HF is achieved by selecting each parameter variation's optimum. In cases of multiple local optima, one optimum is selected. All maintenance strategies are assigned with a consistent inspection interval of 18 FC in order to make the results comparable. The configurations of the maintenance strategies are given in Table 5.5.

Table 5.5: Overview of the maintenance strategies

	Conventional case	**Conventional case with HF optimization**	**Automated case**	**Automated case with HF optimization**
age	48	25	48	25
t_{day}	05:00	12:00	05:00	12:00
EL	2	5	2	5
TL	4	4	4	4
NC	2	1	2	1
EC	OFCW	IB	OFCW	IB
PD	standard	individual	standard	individual
MM	manual	automated	manual	automated
IT	18	18	18	18

The conventional state-of-the-art case is already given by the RC which represents a specific operational scenario for the manual tire maintenance task. This parameter combination has already been calculated in Subsection 5.1.8. The remaining configurations are once again calculated 50 times and the mean values of the results, which are presented in the following section, serve as comparison.

5.3 Evaluation and Discussion

The cost saving potential of each strategy compared to the conventional maintenance process is given in Table 5.6.

Table 5.6: Maintenance cost saving potential for different maintenance strategies

Scenario	PCM	PR	Saving potential
Conventional case	0.499	0.925	0%
Conventional case with HF optimization	0.942	0.991	64%
Automated case	1.0	0.925	63%
Automated case with HF optimization	1.0	0.991	67%

By optimizing HF parameters for the conventional case, 64% of the maintenance cost can be saved. With the use of the TPIS without any HF optimization, a similar cost saving of 63% can be achieved. In this study, the highest cost saving potential is presented by the automated case with HF optimization offering a cost saving of 67% compared to the conventional case. As can be seen in Table 5.6, perfect maintenance or mathematically translated performance efficiency of one can only be reached by applying the TPIS. It was assumed that human error can never be completely eliminated and therefore the highest performance efficiency of one can never be reached by a mechanic.

In the following, the optimal maintenance strategy is discussed with regard to its plausibility on basis of the defined assumptions. The optimized solutions of the parameters age, training level and number of certifications can be realized in maintenance strategies by airlines in order to reduce maintenance cost. However, higher qualifications are associated with higher costs represented by the salary of the mechanic. It still has to be investigated up to which qualification additional salary cost can be justified. Currently, the IM module lacks a link between the age of a mechanic and the experience gained. Therefore, the solution to hire a young professional with years of experience exceeding the actual age of the mechanic is impossible. In addition, a link between training level and experience level can be considered. However, it has to be clarified whether such a correlation exists or a lack of experience can be compensated with additional or above-average training.

A strict pursuit of the optimal solutions of time-of-day and environmental condition is not practicable. If an airline were to carry out all maintenance tasks at a fixed time only, or if an airline were to build an infinite number of hangars in order to operate all aircraft under optimal environmental conditions, the airline's costs would significantly exceed the considered maintenance costs and would therefore not be an optimal solution for the airline. It has to be investigated if additional personal at that time of day could make a difference in maintenance cost and up to which limit additional facility costs would justify the possibility to conduct maintenance tasks more precisely within hangars.

The parameter study has been conducted with an abbreviated version of the simulation framework. This study therefore suggests an increase in inspection interval. However, Meissner et al. have demonstrated that more frequent tire pressure checks and thus a smaller inspection interval show a better impact on the overall maintenance cost (Meissner et al. 2020). Therefore, a further parameter study with the complete simulation framework is necessary to develop appropriate maintenance strategies.

The procedure design has a strong impact on maintenance cost and the optimal design can easily be implemented. Nevertheless, this parameter has to be examined with additional acquisition and labor costs of engineers. A new parameter study is then necessary to select the most economic design.

Furthermore, hidden costs such as acquisition cost for the TPIS and increased fuel consumption costs because of the weight gain by implementation of a TPIS have to be included in the cost estimations to receive more accurate prescriptive maintenance strategies.

6 Conclusion and Outlook

The first goal of this thesis was the development of a stakeholder model to represent the complete maintenance process of an automated TPIS. Based on literature research, the stakeholders operator, CAMO, aircraft maintenance (including base and line maintenance), logistic provider, shop maintenance, and mechanic have been identified. In comparison to the existing stakeholder model, which is implemented in the DLR's simulation framework, it has been determined that the stakeholders logistic provider and shop maintenance need to be added in order to represent the complete maintenance process of the TPIS. As the developed model serves programming purposes, an overview of all stakeholder modules was first presented before transforming each stakeholder into an agent class structure with functions and attributes.

The second goal of this thesis was the enhancement of the existing simulation framework by an imperfect maintenance module. For this purpose, an imperfect maintenance module has been created, allowing the assessment of a system's condition after maintenance. This assessment distinguishes between imperfect and perfect maintenance. A normal distribution has been used to generate random pressure values for imperfect tire pressure checks. The imperfectness of the tire restoration task has been implemented with the virtual age method. The degree of imperfectness in both cases has been obtained with the HEART method, which enables the assessment of human factors.

Within the imperfect maintenance module, different parameters including age, training level, experience level, number of certifications, time-of-day, procedure design, and environmental condition have been implemented. Since an extensive modification of the DLR's existing simulation framework for the attachment of the imperfect maintenance module would have exceeded the scope of this thesis, it has been decided to use an abbreviated version of the simulation framework to demonstrate the functionalities of the imperfect maintenance module.

For the development of prescriptive maintenance strategies for the TPIS, the results of a sensitivity analysis have been used. This was carried out by means of a parameter study using the abbreviated version of the simulation framework. Each parameter of the developed IM module has been gradually varied to detect its impact on maintenance cost. The costs have been analyzed according to the varying frequencies of maintenance tasks performed. The results indicated that poorer performance led mainly to costly detailed inspections or replacements. Subsequently, the parameters have been ranked according to their importance for prescriptive maintenance strategies. The three highest rated human factor parameters were experience level, process design, and time-of-day. The overall goal of the thesis was the evaluation of prescriptive maintenance strategies for the TPIS assuming imperfect maintenance. For this purpose, two maintenance strategies for the TPIS were derived from the sensitivity analysis: TPIS application with and without human factor optimization. Additionally, the maintenance strategy of the conventional state-of-the-art inspection method in combination with human factor optimization has been established for a holistic evaluation. These strategies are a result of the sensitivity analysis, in which the cost optimum of each parameter has been identified. The established strategies have been compared with the defined state-of-the-art scenario in order to determine potential cost savings when applying the respective strategy. Compared to the state-of-the-art scenario, the application of the TPIS in addition to human factor optimization indicated the highest cost savings potential of 67 percent.

In this thesis, the developed stakeholder model was not implemented in the simulation framework, since it was not the aim of this work. Nevertheless, an implementation of the model enables the development of prescriptive maintenance strategies assuming imperfect maintenance in a more precise stakeholder environment. Therefore, first the missing stakeholders shop maintenance and logistic provider have to be implemented in the DLR's existing simulation framework. Next, a detailed analysis of each individual stakeholder has to follow in order to further refine the model and enable the evaluation of even more precise prescriptive maintenance strategies.

A number of important human factors such as stress have been neglected for the IM module due to time constraints. Furthermore, the human factor categories organization and supervision have been left out of the analysis, which also could have strong effects on imperfect maintenance and, hence, on maintenance cost.

The parameter PE adjusted for experience level, training level, and number of certification was based on a performance study on employees working for a Korean financial corporation. A translation to the aviation industry, and thus, to the performance evaluation of maintenance mechanics, was not completely suitable. Nevertheless, this translation has been made due to lack of more suitable data. Further literature research or suitable studies are necessary to evaluate the real impact of the respective parameters on imperfect maintenance. In this thesis, it has been assumed that HEART's shaping factors, and therefore, the human factor parameters of the IM module were independent. Nevertheless, a correlation between these has already been illustrated by (Park et al. 2020).

The established maintenance strategies have been based on the objective of the maintenance cost. In order to identify the best possible maintenance strategy for an airline, further costs such as training cost, mechanic salaries, facility cost, and acquisition cost should be additionally considered when establishing maintenance strategies.

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Statement of Authorship

I declare that I completed this thesis on my own and that information which has been directly or indirectly taken from other sources has been noted as such. Neither this nor a similar work has been presented to another examination committee and has not been published.

Garching, September 30, 2020

Vida Kohestani Nejad

A Appendix: HEART Tables

The following HEART tables are taken from (Williams 1988, Cassis 2018) and were updated by (Bell & Williams 2017).

A.1 Generic Task Unreliability Table

#	Task Type	Nominal HEP
A	Totally unfamiliar, performed at speed with no real idea of likely consequences	0.55
B	Shift or restore system to a new or original state on a single attempt without supervision or procedures	0.26
C	Complex task requiring high level of comprehension and skill	0.16
D	Fairly simple task performed rapidly or given scant attention	0.09
E	Routine, highly practiced, rapid task involving relatively low level of skill	0.02
F	Restore or shift a system to original or new state following procedures, with some checking	0.003
G	Completely familiar, well-designed, highly practiced, routine task occurring several times per hour, performed to highest possible standards by highly motivated, highly-trained and experienced person, totally aware of implications of failure, with time to correct potential error, but without the benefit of significant job aid	0.0004
H	Respond correctly to system command even when there is an augmented or automated supervisory system providing accurate interpretation of system stage	0.00002
M	Miscellaneous task for which no description can be found	0.03

A.2 Error Producing Conditions Table

#	Error Producing Condition	Multiplier
1	Unfamiliarity with a situation which is potentially important, but which only occurs infrequently or which is novel	17
2	A shortage of time available for error detection and correction	17
3	A low signal-to-noise ratio	10
4	A means of suppressing or overriding information or features which is too easily accessible	9
5	No means of conveying spatial and functional information to operators in a form which they can readily assimilate	8
6	A mismatch between an operator's model of the world and that imagined by a designer	8
7	No obvious means of reversing an unintended action	8
8	A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information	6
9	A need to unlearn a technique and apply one which requires the application of an opposing philosophy	6
10	The need to transfer specific knowledge from task to task without loss	5.5
11	Ambiguity in the required performance standards	5
12	A mismatch between perceived and real risk	4
13	Poor, ambiguous or ill-matched system feedback	4
14	No clear, direct and timely confirmation of an intended action from the portion of the system over which control is to be exerted	3
15	Operator inexperience (e.g. a newly-qualified tradesman, but not an expert)	3
16	An impoverished quality of information conveyed by procedures and person-person interaction	3
17	Little or no independent checking or testing of output	3

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#	Error Producing Condition	Multiplier
18	A conflict between immediate and long-term objectives	2.5
19	No diversity of information input for veracity checks	2.5
20	Mismatch between the educational-achievement level of an individual and the requirements of the task	2
21	An incentive to use other more dangerous procedures	2
22	Little opportunity to exercise mind and body outside the immediate confines of a job	1.8
23	Unreliable instrumentation (enough that it is noticed)	1.6
24	A need for absolute judgments which are beyond the capabilities or experience of an operator	1.6
25	Unclear allocation of function and responsibility	1.6
26	No obvious way to keep track or progress during an activity	1.4
27	A danger that finite physical capabilities will be exceeded	1.4
28	Little or no intrinsic meaning in a task	1.4
29	High-level emotional stress	1.3
30	Evidence of ill-health among operatives, especially fear	1.2
31	Low workforce morale	1.2
32	Inconsistency of meaning of displays and procedures	1.2
33	A poor or hostile environment (below 75% of health or life-threatening severity)	1.15
34A	Prolonged inactivity or highly repetitious cycling of low mental workload tasks	1.1 for first hour
34B	Prolonged inactivity or highly repetitious cycling of low mental workload tasks	1.05 for each hour there
35	Disruption of normal work-sleep cycles	1.1
36	Task pacing caused by the intervention of others	1.06
37	Additional team members over and above those necessary to perform task normally and satisfactorily	1.03

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#	Error Producing Condition	Multiplier
38	Age (between 25-85) of personnel performing perceptual tasks	1.16 for each 10 years
39	Variation between diurnal high & low of performance	2.4
40	Distraction or task interruption	4