COST AND BENEFIT OF SCHEDULED STRUCTURAL HEALTH MONITORING FOR COMMERCIAL AIRCRAFT

Dominik M. Steinweg and Mirko Hornung

Bauhaus Luftfahrt e.V., 82024 Taufkirchen, Germany

Abstract

Structural health monitoring (SHM) has been discussed as a promising solution to improve the cost and safety performance of aircraft since the 1950s. However, its current use in commercial aviation is still limited to field tests due to an unclear business case. To this end, the work at hand contributes to the understanding of the business case connected to structural health monitoring in commercial aviation by conducting an integrated cost-benefit study. This study considers a geometric approximation of a selected reference aircraft, airframe fatigue as primary driver for scheduled structural inspections, generalized SHM performance represented by a receiver operator characteristic curve, SHM equipment weight, fuel burn, lost revenue due to decreased payload capacity and decreased airframe weight due to the perspective removal of access panels. It shows that the use of SHM during scheduled inspections can improve the overall operating cost of the considered reference aircraft. However, the existence and magnitude of a benefit depends heavily on the SHM equipment weight, monitoring performance and installation cost of the respective SHM system.

Keywords: Structural Health Monitoring, Cost Benefit Analysis, Integrated Analysis Framework

1. Introduction

Since the liberalization of the worldwide air transport market, airlines are faced with ever-increasing levels of competition [2, 3]. Productivity improvements across the entire value creation process are therefore key to success in commercial aviation [4]. With their combined contribution of up to two thirds of Direct Operating Cost (DOC), fuel consumption and maintenance expenditures provide significant leverage in improving the financial performance of aircraft [5, 6]. In this regard, structural health monitoring (SHM) presents a technology proposed over 70 years ago, that has the potential to enable lighter airframes and thus reduce fuel burn as well as improve the execution of structural maintenance [7]. Even though numerous SHM concepts have been presented over time, with few being tested in service, available studies on cost advantages still do not find consistent results [8]. To this end, the work at hand shall provide a contribution to understanding the cost and benefit of SHM systems in commercial aircraft, specifically the potential benefits of replacing scheduled structural inspections with SHM.

1.1 Scheduled SHM

Since 2013, a standardized guideline covering the implementation of SHM on fixed wing aircraft has existed with SAE ARP6461 [9]. Here, SHM is recognized as part of the overall *structural health management* along with crew observations, maintenance records and fleet-wide data analysis, as illustrated in Figure 1 [1]. The structural health management itself is considered to be part of the overall *aircraft health management,* together with engine health monitoring and system health management [1]. In this work, only SHM is considered, neglecting possible inputs from other health management systems. At the application level, SHM systems can be divided by their mode of operation and technology type [1]. SHM systems operating in a scheduled way replace manual labor during a scheduled inspection. Automated SHM systems, on the other hand, allow for condition-based maintenance, leading to ad-hoc inspection events outside the predefined inspection program [1]. Depending on the technology utilized, SHM systems can be classified as damage monitoring and operation monitoring [1]. While the boundaries between the two can be fuzzy in practical applications, the work at hand only considers damage monitoring. The Maintenance Steering Group 3 analysis employed to derive scheduled maintenance requirements first recognized SHM in its 2009.1 revision over a decade ago [10]. Therefore, the work at hand investigates only scheduled SHM.

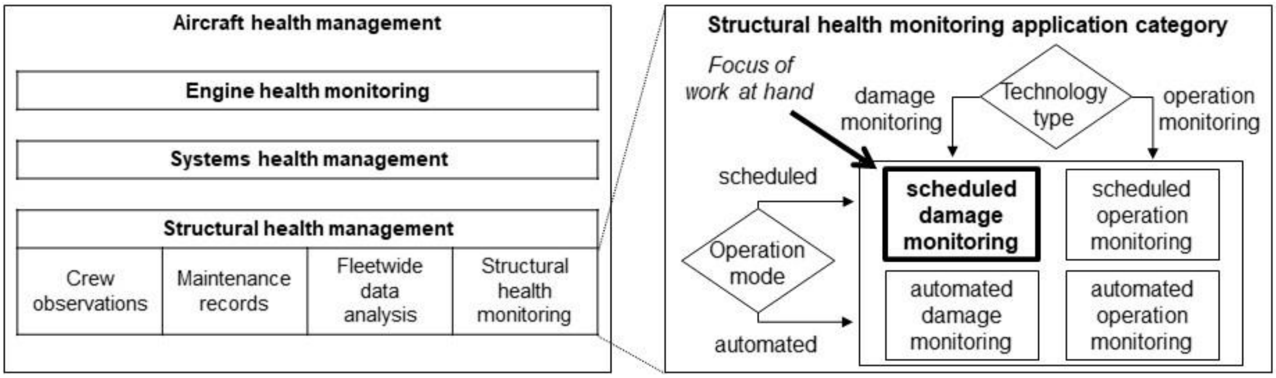


Figure 1 – Classification of SHM within the overall aircraft health management (left) and systematic of SHM approaches itself (right), adapted from [1].

1.2 Cost and Benefit Studies on SHM

The cost and benefit of SHM in commercial aviation has already been the subject of numerous investigations, which yielded varying results [11]. For a Boeing 737, an SHM system is sized to inspect the frames and stringers of the airframe, demonstrating substantial inspection time savings [12]. However, the same work suggests that increased fuel burn and lost revenue resulting from the introduction of SHM equipment increase the overall aircraft operating cost [12]. Based on a Monte Carlo simulation, it is suggested that progressive inspections based on SHM decrease the associated cost by 50 percent compared to regular scheduled inspections [13]. Subsequent work by the same author also indicates reduced levels of fatigue risk [14]. A 30 percent reduction of inspection and maintenance costs associated with the use of SHM is also found by [15]. Using SHM as part of predictive maintenance can improve inspection cost by 67 percent, without considering the impact of SHM equipment weight [16]. In order to link component properties and SHM characteristics with the financial impact on the operation of aircraft, this work utilizes an integrated analysis framework.

2. Materials and Methods

In order to quantify the economic impact of scheduled SHM on a representative commercial reference aircraft, a techno-economic assessment framework is proposed. The methodology is based on a series of individual models addressing dedicated aspects connected to the usage of SHM. (1) The aircraft model contains a simplified airframe geometry and inspection requirements for the reference aircraft considered. (2) The overall airframe geometry consists of individual structural components, for which structural fatigue is simulated over the entire lifetime of the aircraft. Additionally, aircraft systems are considered when scheduled inspections of the reference aircraft are planned and conducted. (3) Subsequently, the capabilities of a scheduled SHM system are simulated, for a varying SHM monitoring performance of a generic sensor system. Additionally, varying SHM system weights are considered. (4) Using the built-in capability of SHM, selected changes in structural inspection requirements and thus airframe design are discussed. (5) To consider the impact of SHM equipment weight and suggested aircraft design changes on fuel cost, a simplified fuel burn model is introduced. (6) In the next step, the operation of the aircraft is simulated, in which the aircraft follows a predefined flight plan amounting to 60,000 flight hours and 30,000 flight cycles over its entire lifetime. Regular inspections and maintenance are also conducted. (7) A cost model is introduced to translate the operational performance of the aircraft to its operating cost, before (8) the method is validated using reference values from the scientific literature. The individual steps of the methodology, key figures and assumptions, as well as intermediate results, are presented in Figure 2.

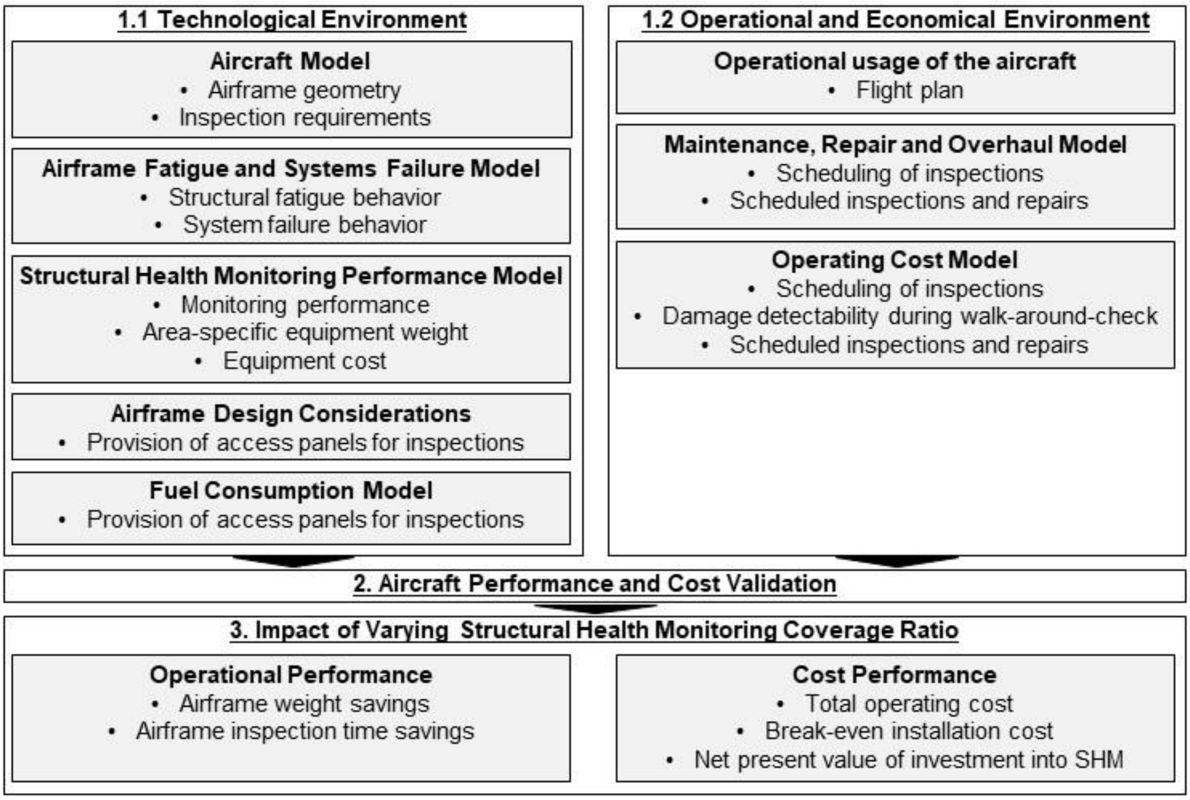


Figure 2 – Utilized approach to quantify the cost and benefit of scheduled SHM in commercial aviation.

2.1 Aircraft Model

The aircraft model assumed contains a geometrical representation of the airframe as well as inspection requirements for both the airframe and aircraft systems and power plants. Due to its commercial success and widespread usage, the Airbus A320 aircraft is selected as the reference aircraft for this work. The structure of the aircraft model follows the Airbus A320 Maintenance Planning Document (MPD). This document is produced in a standardized process by the manufacturer in accordance with authorities, operators, maintenance organizations and important suppliers, and is comprised of individual inspection tasks containing the frequency and scope of inspections of individual positions of the aircraft [17]. An excerpt from this document is shown in Table 1. Using the frequency limits provided in calendar time, FC or FH for each task, the maintenance program for a specific aircraft can be established.

Table 1: Sample inspection task excerpt contained in Airbus A320 MPD [18].

Task number	Zone	Position	Description	Task code	Skill code	Threshold interval	Man-hours
282801-01-1	151 / 152	ACT EXTERNAL SURFACE	Detailed inspection of additional center tank external surface …	AF	DI	T: 6 YE I: 6 YE	0.8

Using publicly available resources, the structural surface of all airframe positions referenced in the MPD is reconstructed. This results in a total surface area of the reference aircraft of 1,966 m². However, the validation of the specified airframe surface area for the reference aircraft used as part of this work is based on a series of assumptions. All aircraft positions are assumed to be assembled from sheet-like components. For composite structures, a sheet thickness of 4.5 mm and density of 1,500 kg/m is assumed. For metallic structures, a sheet thickness of 3.5 mm and density of 2,800 kg/m is assumed. The resulting sheet area und associated structural weight is shown in Table 2. The resulting airframe weight deviates by less than 2 percent compared to the weights specified in [19] and [20].

Table 2: Breakdown of structural surface areas considered in the geometry model of the reference aircraft by ATA chapter.

ATA chapter [-]	Material [-]	Sheet area [m^2]	Weight [kg]	Share [%]
53 - Fuselage	Composite	325.6	2,197.9	12.4
53 - Fuselage	Aluminum	800.5	7,844.7	44.2
54 - Nacelles/Pylons	Composite	22.0	148.8	0.8
54 - Nacelles/Pylons	Aluminum	189.0	1,852.2	10.4
55 -Stabilizers	Composite	124.8	842.1	4.7
55- Stabilizers	Aluminum	93.0	911.5	5.1
57 - Wings	Composite	21.5	144.9	0.8
57 - Wings	Aluminum	389.9	3,821.5	21.5
Subtotal	Composite	493.9	3,333.6	18.8[a]
Subtotal	Metal	1,472.4	14,429.9	81.2[b]
Total	-	1,966.30	17,763.4[c]	100

[a] Estimated share of composite materials 1.3 percent lower than in [19].
[b] Estimated share of metallic materials 0.3 percent higher than in [19].
[c] Estimated total airframe weight is 1.9 percent lower than the total of 18,103 kg given in [20].

2.2 Airframe Fatigue and Systems Failure Model

For every structural position of the airframe considered, fatigue damages are simulated based on a Paris-Erdogan crack growth approach, described in detail in [21]. As the exact geometry and loads on the individual structural components of the aircraft are not considered as part of this work, a simplified approach is used to model the principle crack length of every structural component. The non-dimensioned crack length $\hat{a}_N$ after N cycles, where $\hat{a}_N = 100\%$ equals critical crack growth, which is defined here as fatigue damage, is given by

$$\hat{a}_N = \left(\frac{1}{\frac{1}{\hat{a}_0 \cdot \left(\frac{m}{2}-1\right)^{-1}} - N \cdot \left(\frac{m}{2}-1\right) \cdot C \cdot \left(\Delta\sigma\sqrt{\pi}Y_I\right)^m + 1} \right)^{\frac{1}{\frac{m}{2}-1}} . \quad (1)$$

Thus, $\hat{a}_0$ is the initial crack length, $m = 3$ and C material-dependent parameter, $\Delta\sigma$ the changing normal stress, Y_I the geometry factor. Component-specific parameters are combined in a single crack growth factor $C\left(\Delta\sigma\sqrt{\pi}Y_I\right)^m$, which can be calculated by

$$C \cdot \left(\Delta\sigma\sqrt{\pi}Y_I\right)^m = \frac{1}{\left(\frac{m}{2}-1\right) \cdot N_c} \cdot \left(\frac{1}{\hat{a}_0^{\frac{m}{2}-1}} - \frac{1}{\hat{a}_c^{\frac{m}{2}-1}} \right), \quad (2)$$

where N_c is the cycle in which the critical crack occurs. Since N_c is unknown, it is assumed that $N_c = T_I + 6 \cdot I_I$, where T_i is the inspection threshold and I_I the inspection interval given in the MPD. The initial crack length $\hat{a}_0$ is calculated by

$$\hat{a}_0 = \left(\frac{1}{(N_c + T_i) \cdot \left(\frac{m}{2}-1\right) \cdot C \cdot \left(\Delta\sigma\sqrt{\pi}Y_I\right)^m + 1} \right)^{\frac{1}{\frac{m}{2}-1}} . \quad (3)$$

The schematic crack growth of an individual part is summarized in Figure 3.

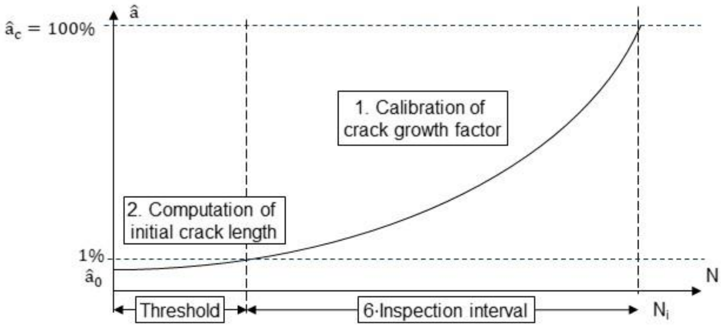


Figure 3 – Calibration of crack growth factor and initial crack length of structural components.

The approach used to calibrate the crack growth factors is arbitrarily based only on the inspection requirements specified in the MPD. However, inspection frequencies provided in the MPD can be driven by the severity of damage rather than crack growth speed. The assumed crack growth factors are therefore limited to the 97.5th percentile, as shown in Figure 4, to avoid rapid fatigue in a few selected parts.

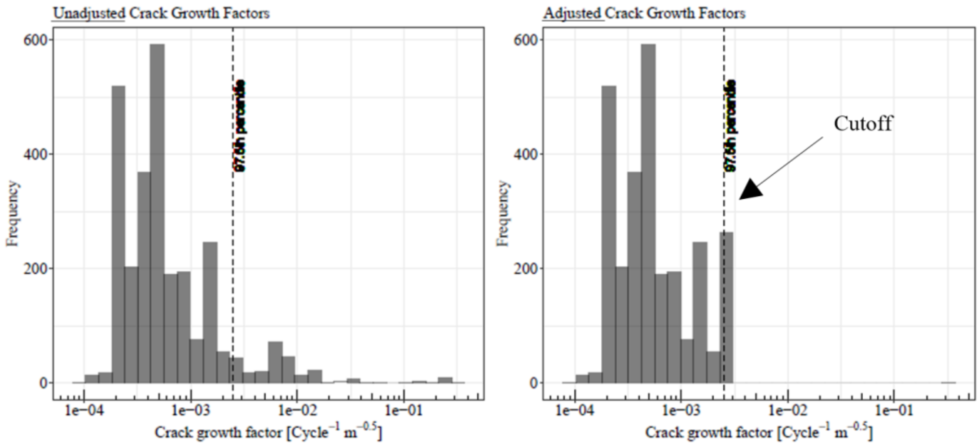


Figure 4 – Histogram of utilized crack growth factors in the Paris-Erdogan-based crack growth model before (left) and after (right) the crack growth factors have been adjusted.

As $\hat{a}_0$ is nondeterministic in practice, a normal distribution of $\hat{a}_0$ is assumed in this work. The standard deviation $\hat{\sigma}_{a_0}$ of this distribution is assumed to be

$$\hat{\sigma}_{a_0} = \hat{a}_0^{0.25}. \tag{4}$$

The probability of a damaged structure after N cycles can thus be expressed as

$$P\big(\hat{a}_c(N)\big) = \int_1^{\infty} \left(\left(\frac{1}{\sigma_{a_0} \cdot \sqrt{2\pi}} \cdot e^{-0.5\left(\frac{\hat{a}-\hat{\mu}}{\sigma_{\hat{a}_0}}\right)^2} \right)^{1-\frac{m}{2}} - N \cdot \left(\frac{m}{2} - 1\right) \cdot C \cdot \left(\Delta\sigma\sqrt{\pi} Y_I\right)^m + 1 \right)^{-\frac{1}{\frac{m}{2}-1}} d\hat{a}. \tag{5}$$

The occurrence of structural failures is then simulated using binominal sampling. Binominal sampling is also used to simulate the occurrence of system failures. Therefore, a MTBF of 90,000 flight hours is assumed for every *position of the aircraft* referenced in systems and power plant program of the MPD. The probability of a failure is then calculated by

$$p_{Failure}(N) = e^{-\frac{N-1}{MTBF}} - e^{-\frac{N}{MTBF}}. \tag{6}$$

2.3 Scheduled SHM Performance Model

The inspection tasks described in the MPD can be performed either manually, as they currently are, or by means of built-in SHM, which is used during a scheduled inspection. The SHM system is considered a binary classifier in this work. For a given monitoring system, a damage classification threshold can be selected. The performance of the classifier can be expressed by its receiver operator characteristic curve, which is assumed in this work by

$$y = x^{\frac{1}{\theta}}, \tag{7}$$

where y describes the true positive rate of the classifier, x the false positive rate of the classifier and θ the performance of the classifier [22–24]. For a random classifier, it holds that $\theta = 1$, while for a perfect classifier, $\theta \to 0$. In practice, the sensor uses a cutoff threshold to determine the underlying condition associated with the measured signal. When y and x are observed for a variety of different thresholds, a receiver operator characteristics curve can be plotted. This approach is summarized in Figure 5. Damage detectability can be bought at the expense of false alarms, or vice versa.

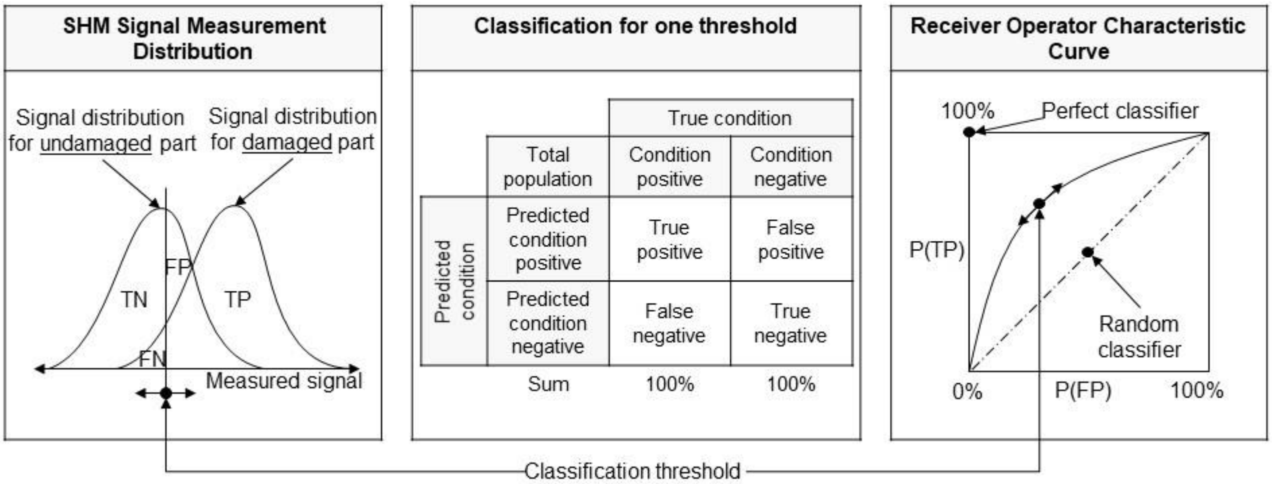
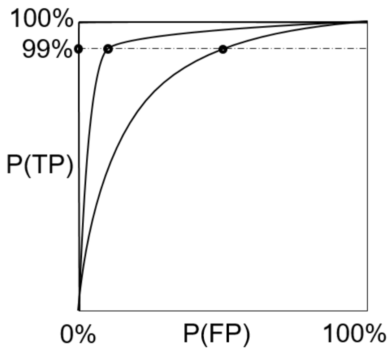


Figure 5 – Classification thresholds applied to a SHM signal measuring distribution are used to illustrate the receiver operating characteristic curve, which represents the ratio of true and false positive classifications for a varying classification threshold.

The practically achievable performance depends on a series of environmental and structural factors such as temperature, material, loads, expected types of damage and so on [25]. Therefore, the performance considered approximately covers the expected performance bandwidth rather than exactly specifying it.



Study	False Positive Rate [%]	True Positive Rate [%]
1	0	99
3	10	99
4	50	99

Figure 6 – Assumed performance of investigated SHM system.

Depending on the application, different sensor systems have been previously presented. In a study for the Boeing 737, comparable to the selected reference aircraft in size, the total SHM system weight has been specified as 1,000 lb when only the stringers and frames of the aircraft are monitored [12]. The same weight would correspond to a specific equipment weight of approximately 0.23 kg/m² for the reference aircraft. As the area-specific weight of the SHM system is unknown, it is assumed to be between 0 kg/m² and 3 kg/m² in this study.

2.4 Airframe Design Considerations

It has been suggested that SHM can improve the airframe weight through new design requirements in numerous ways. In [26], SHM has been suggested to improve the weight of structural components designed for fatigue, until another sizing limit such as impact damages becomes relevant. Continuously growing fatigue damages are then detected by SHM before they become critical. With regard to the structural maintenance process itself, scheduled SHM can be used to substitute manual inspections. Therefore, structural design requirements given in CS 25.611, which require the manufacturer to design for inspectability, indirectly mandate the use of inspection cutouts and doors. Depending on the position and loading condition, cutouts can be used to decrease the weight of a lightly loaded beam [27]. However, in moderately and heavily loaded beams as well as skin-stringer panels, the provision of a cutout or access door increases structural weight as stiffeners, doublers or additional structural members are required [27]. To this end, SHM can fulfill inspection requirements and make cutouts obsolete, if they are only used for structural inspections. However, in the case of actual damages, corrective work may be more complicated due to the lack of access doors. Based on empirical studies, the weight of access panels on pressurized and unpressurized parts of the aircraft are given in [20]. For this study it is assumed that the use of SHM can fulfill the inspectability requirements stated in CS 25.611 which currently require the provision of access doors at some areas of the aircraft. In the MPD, access zones on the aircraft are defined, specifying the area of the aircraft in which the work is conducted. If only tasks contained in the structural program are performed in a specific area and thus all maintenance is replaced by SHM, it is assumed that the access panel can be discarded, making the structure lighter. For the unpressurized access panels on the fuselage of the F-4, F-104 and F-105 fighter aircraft, the area-specific weight of the access panel is between 8.3 and 28.2 kg/m² [20]. The weight of emergency doors is specified as between 5.8 and 25.3 kg, based on the analysis of 14 passenger jet aircraft [20]. Even though this approach neglects the exact geometry, size and loads of a specific cutout, it allows an initial estimate of the possible structural weight savings if all maintenance tasks behind a specific access door are covered by SHM.

2.5 Fuel Consumption Model

Using the Breguet range equation, the total required fuel mass m_t for a given range R is given by

$$m_t = m_{ZFW} \cdot \left(e^{\frac{R \cdot b_F \cdot g}{E \cdot V}} \right), \quad (8)$$

where m_{ZFW} is the zero fuel weight of the aircraft, b_F the thrust specific fuel consumption, g the gravitational constant, E the glide ratio of the aircraft and V its velocity. Assuming the same range for a flight with and without SHM equipment, the corresponding change in required fuel mass is given by

$$\frac{m_{t,SHM}}{m_t} = \frac{m_{ZFW} + m_{SHM} - \Delta m_{Airframe}}{m_{ZFW}}, \quad (9)$$

where $m_{t,SHM}$ is the total required fuel mass for aircraft equipped with SHM, m_{SHM} the mass of the SHM equipment itself and $\Delta m_{Airframe}$ the decreased airframe weight.

2.6 Aircraft Usage

The scheduling and thus frequency of inspections conducted on the reference aircraft are driven by the length of each flight cycle of the reference aircraft. To improve the representativeness of the study, the assumed usage for the reference aircraft is equal to the median of the Airbus A320 fleet, as illustrated in Figure 7.

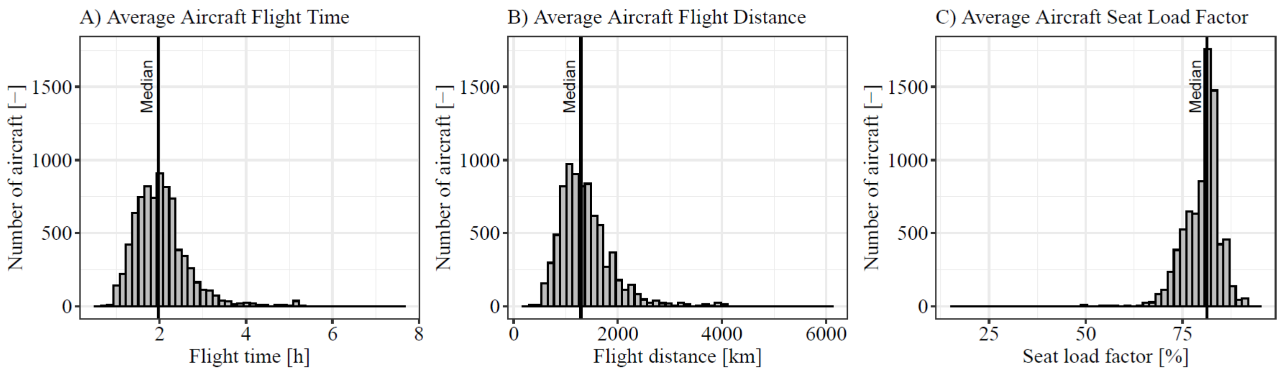


Figure 7 – Distribution of A) aircraft flight time and B) aircraft flight distance of Airbus A320 aircraft based on 16,625,103 flights for 7,952 different aircraft over a period of 797 days between September 23, 2017 and November 29, 2019. C) Distribution of Airbus A320 load factors served on respective routes based on Sabre data for 2019.

2.7 Maintenance Repair and Overhaul Model

As the MPD only specifies individual inspection tasks, the scheduling of inspection events has to be performed for each aircraft individually. In this work, a straightforward approach is used to schedule maintenance events. The maximum time between two consecutive events is defined by the shortest inspection interval of a specific task. All other tasks falling in between the current and next inspection, which would therefore effectively shorten the inspection interval, are preponed to the current inspection. The scheduling approach used in this work is illustrated in Figure 8. The overall inspection time of a single event is calculated by summarizing the amount of work specified in the MPD. As the MPD considers the aircraft to be in a general maintenance condition before an inspection, the time required for tool preparation, work order planning and generally everything that is not performed directly on the aircraft is neglected. Therefore, the inspection times specified in the Airbus A320 MPD are arbitrarily doubled before they are used in the presented cost benefit study.

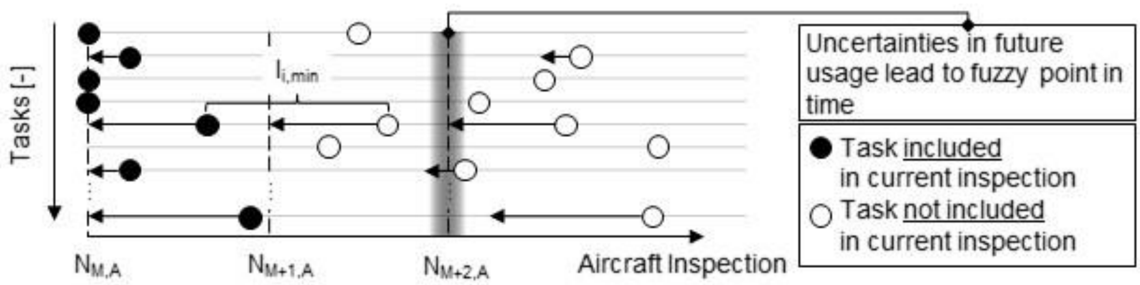


Figure 8 – Planning of scheduled inspections based on maintenance tasks contained in MPD.

2.8 Operating Cost Model

The assumed operating costs are based on US DOT form 41 data, submitted by 38 airlines between the years 1990 and 2020. The considered costs are inflation adjusted to the year 2020. The breakdown of the assumed overall operating cost is summarized in Table 3.

Table 3: Cost model based on DOT form 41 data for

Cost component [-]	Cost [USD/FH]	Considered SHM impact [-]
Crew	694.6	
Fuel	1,889.0	Added SHM equipment weight. Reduced airframe weight through decreased number of access doors.
Hull insurance	6.4	
Miscellaneous flying operations	79.2	
Subtotal flying operations	*(2,669.2)*	
Airframe materials	53.0	
Airframe repairs	134.0	
Aircraft engines	181.9	
Deferrals and provision	188.5	
Airframe inspections	95.0	Decreased time for manual inspections.
Applied maintenance burden	176.4	
Net obsolescence	7.1	
Subtotal maintenance	*(835.9)*	
Reduced revenue generation	0	Reduced payload.
Total cash operating cost	***3,505.1***	

2.8.1 SHM Impact on Fuel Cost

The fuel cost $C_{Fuel,SHM}$ for a reference aircraft using SHM is calculated by

$$C_{Fuel,SHM} = C_{Fuel} \cdot \frac{m_{ZFW} + m_{SHM} - \Delta m_{Airframe}}{m_{ZFW}}, \quad (10)$$

where C_{Fuel} is the cost of fuel based on the DOT form 41 data, m_{SHM} the mass of the SHM system and $\Delta m_{Airframe}$ the change in airframe mass, enabled by the replacement of access doors and m_{ZFW} the weight of the aircraft without fuel, assumed to be 55,800 kg.

2.8.2 SHM Impact on Maintenance Cost

Inspection tasks given in the zonal or structural program of the MPD are either conducted manually or by means of SHM. If the surveilled position is equipped with SHM, the inspection time of the respective position is only considered if the SHM system produces an alarm during a scheduled inspection. The alarm can either be a true positive or a false positive. The overall inspection time of the aircraft is thus given by

$$C_{Insp,Stru,SHM} = C_{Insp,Stru} \cdot \frac{\sum_a^A t_{I,a}}{\sum_i^N t_{I,i}}, \quad (11)$$

where $C_{Insp,Stru,SHM}$ is the structural inspection cost with SHM, $C_{Insp,Stru}$ the structural inspection cost without SHM, $\sum_i^N t_{I,i}$ the total labor time to complete all structural inspection tasks and $\sum_a^A t_{I,a}$ the total labor time of inspection tasks for which an alarm was produced during a scheduled event. The cost for airframe materials, airframe repairs, engines, deferrals and provisions, applied maintenance and net obsolescence are assumed to be not influenced by SHM.

2.8.3 SHM Impact on Aircraft Revenue Generation Capabilities

Moreover, added SHM equipment weight impacts the payload capacity of the aircraft adversely. If the SHM system is introduced during the design phase of the aircraft ceteris paribus, the additional equipment mass requires a resizing of the aircraft, leading to additional system, engine and possibly structural weight, thus further increasing fuel burn. If SHM is considered as retrofit system for an existing aircraft, as in this work, the SHM weight reduces the payload capacity and thus the opportunity to generate revenue. However, the magnitude of this effect depends on the payload and range distribution serviced by the airline. In cantilever wing aircraft, the maximum payload is effectively limited by the maximum zero fuel weight (MZFW) and maximum takeoff weight (MTOW). Only if an airline uses the entire load capacity of the aircraft does the reduced payload decrease the revenue generation capability. Second, the location within the aircraft where the SHM system is installed determines if the equipment weight is considered exclusively as part of the aircraft zero fuel weight (ZFW) or takeoff weight (TOW). Weight added to the wing is not considered part of the ZFW, but only TOW. However, the MTOW limits the payload for missions beyond a certain range. Therefore, the impact of retrofit SHM equipment weight on the revenue-generating capability of aircraft depends on the distribution of typical payloads and ranges, as illustrated in Figure 9. The loss in revenue $\Delta\mathrm{Rev}$ from SHM equipment installed on the wing is based on [28] and calculated by

$$\Delta Rev = Rev \begin{cases} 0, & for\ 0 \leq \Delta_{MTOW} \leq 2\% \\ 4.8333 \cdot \Delta_{MTOW}^2 - 0.105 \cdot \Delta_{MTOW} + 0.0002, & for\ 2\% < \Delta_{MTOW} \leq 10\%, \\ undefined & for\ 10\% < \Delta_{MTOW} \end{cases} \quad (12)$$

where $\Delta_{MTOW}^2 = \frac{m_{SHM}}{MTOW}$ with MTOW is assumed to be 73,500 kg. The revenue Rev of the aircraft is assumed to be 5,900 USD per flight hour for the reference aircraft. At a median load factor of 81 percent and maximum average load factor of 95 percent, it is assumed that 8 of the 160 seats mostly remain empty. Assuming a passenger weight of 100 kg, the first 800 kg of equipment mass added to the fuselage does not impact the revenue-generating capabilities of the aircraft. For every additional 100 kg, the revenue decreases by $\frac{5900\ USD}{152} = 38.82\ \mathrm{USD}$ per FH.

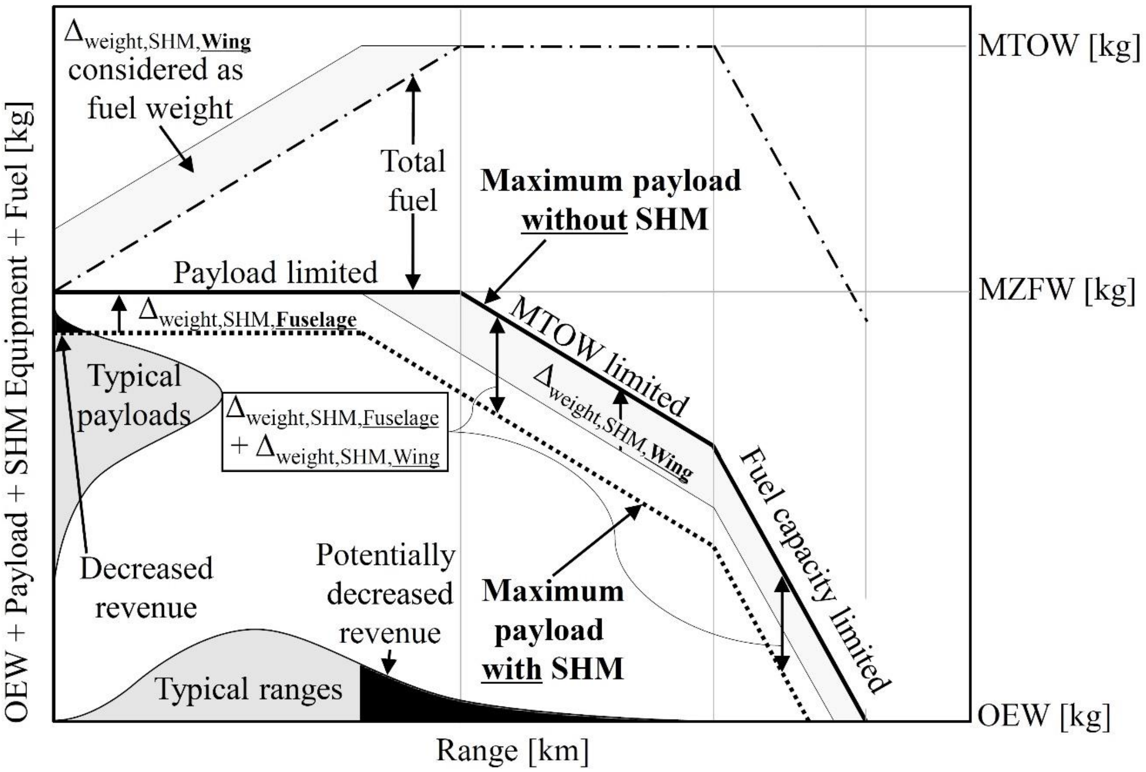


Figure 9 – Impact of retrofitted SHM equipment weight on payload capacity, adapted from [29]. SHM equipment weight added to the fuselage directly decreases the payload capacity of the aircraft. However, weight added to the wing can be considered as fuel weight as it decreases the wing root bending moment of cantilever wing aircraft. Thus, SHM equipment installed on the wing impacts the aircraft payload capacity only on flights operated beyond a range, where the aircraft MTOW is reached.

2.8.4 Net Present Value of Investment

The net present value (NPV) of an investment into SHM is calculated by

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{S_t}{(1+WACC)^t}, \qquad (13)$$

with I_0 being the initial investment, S_t the annual savings in operating cost, $WACC$ the weighted average cost of capital assumed at 8 percent p.a. and n the number of years the SHM system (or aircraft) remains operational.

3. Results

The results produced by this cost-benefit evaluation methodology are presented in the following. In the first part, the operational performance of the reference aircraft is shown, covering the amount of simulated fatigue damages, inspection effort and repair effort. Subsequently, the SHM system is sized before the possibility of removing access panels is further elaborated. Finally, the impact of SHM on aircraft operating cost is presented.

3.1 Operational Performance of Reference Aircraft

For 20 simulation runs, structural components failed 115 times on average (SD=12), while parts in the aircraft system and power plant failed 305 times on average (SD=13). For the reference aircraft, it is arbitrarily assumed that the repair of a position is equal to 125 times the inspection time specified in the MPD for this position, e.g. if an inspection of a structural component requires 6 minutes, the damage repair requires a total of 12.5 hours of labor. As the inspections are scheduled analytically, the total inspection effort is constant for every simulation. A comparison of the simulated inspection and repair time of the reference aircraft and literature is shown in Figure 10.

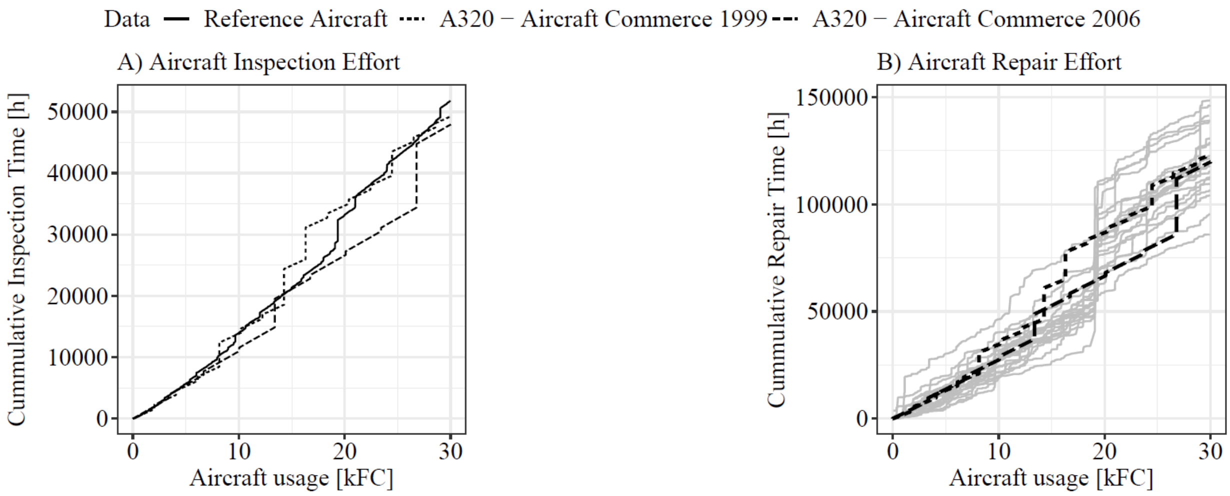


Figure 10 – Comparison of A) cumulated inspection and B) cumulated repair time of reference aircraft to literature [30, 31]. For the literature values, a split between inspection and repair time of 1:2.5 is assumed.

3.2 Sizing Considerations for SHM System

Based on the geometry model utilized, the weight of the SHM system can be derived as a function of the instrumented airframe and covered inspection time. To this end, Figure 11 summarizes the weight of the SHM equipment dependent on the covered airframe surface and the subsequently substituted manual inspection effort. In this work, structural inspection tasks with a higher area-specific inspection time are replaced by SHM first. Note that the assumed weight function is linear. Depending on the geometrical complexity of a structural part, its load environment and materials, this may not necessarily be the case in practice.

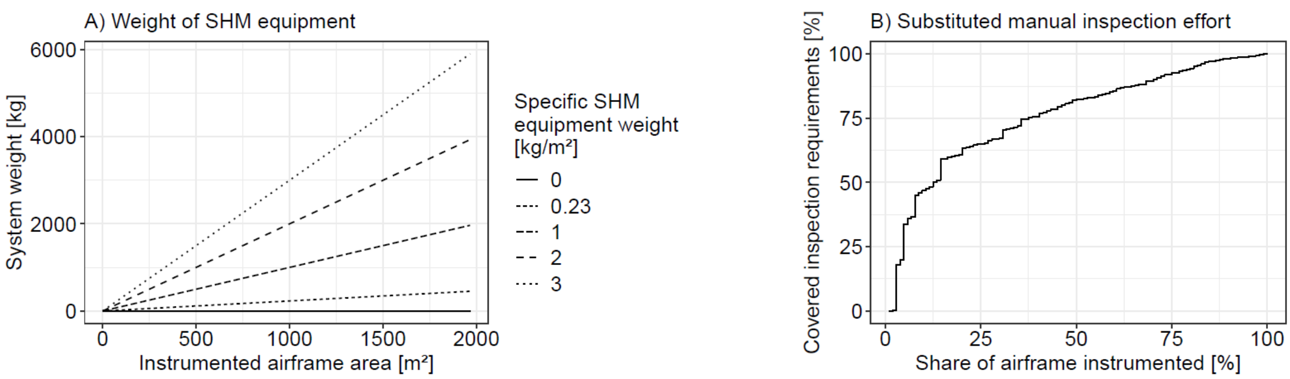


Figure 11 – Weight of SHM as a function of coverage ratio and substituted overall inspection time

Using the information regarding access panels and doors provided in the MPD, access panels used exclusively for structural inspections are identified and summarized in Figure 12.

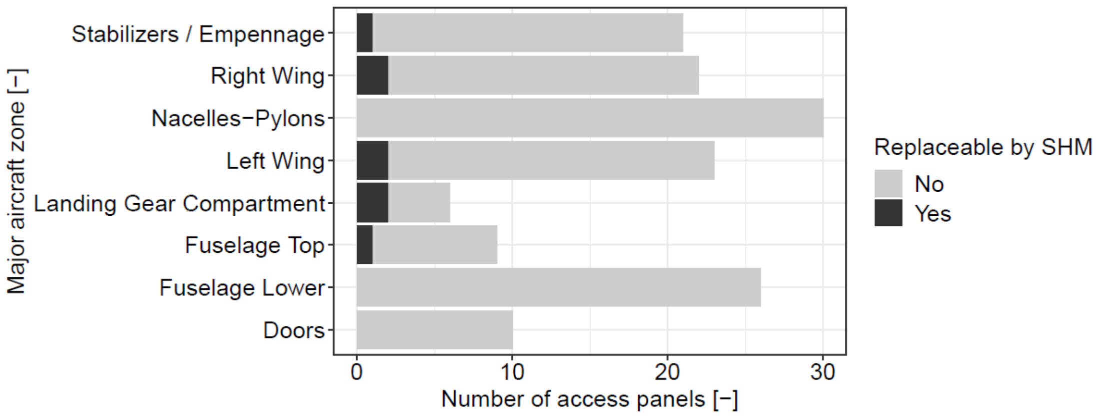


Figure 12 – Access panels replaceable by SHM

The structural surface area behind the access panel on the fuselage top is assumed to be 2.92 m², while the structural surface area behind the access panel on the stabilizers and empennage is 0.49 m². Based on [20], the weight saving for the fuselage access door and empennage access door replacement is assumed to be 5.8 kg each. As the structural surface area behind the other replaceable access panels could not be specified from publicly available resources, their possible replacement is omitted in the following.

3.3 Impact of Scheduled SHM on Aircraft Operating Cost.

The resulting impact of an SHM system on the total operating cost of a scheduled SHM system is illustrated in Figure 13, neglecting only SHM equipment installation cost.

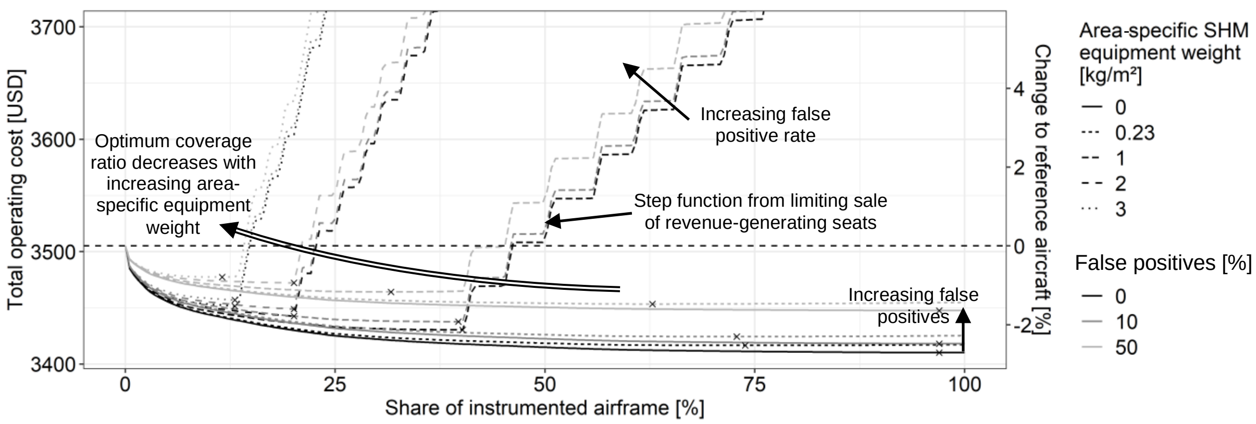


Figure 13 – Impact of scheduled SHM on operating cost per flight hour of reference aircraft. Optimum coverage ratio for every system is marked as “x”.

Depending on the weight of the system and its monitoring performance expressed as false positives, the optimum airframe coverage ratio varies. Based on the results presented, the area-specific break-even installation cost for an SHM system can be specified, depending on its monitoring performance and weight, as presented in Table 4.

Table 4 – Break even installation cost for scheduled SHM system

False positive [%]	Area-specific weight [kg/m²]	Covered airframe area [%]	Total savings [million USD]	Total area-specific savings [USD/m²]
0	0	*97.0	5.70	2,989
0	0.23	73.9	5.32	3,660
10	0	*97.0	5.22	2,739
10	0.23	72.9	4.84	3,381
0	1	40.2	4.49	5,676
10	1	39.7	4.05	5,186
0	2	20.1	3.75	9,491
50	0	97.0	3.46	1,812
10	2	20.1	3.37	8,538
0	3	13.1	3.22	12,540
50	0.23	62.8	3.11	2,516
10	3	13.1	2.89	11,253
50	1	31.7	2.46	3,950
50	2	20.1	1.98	5,002
50	3	11.6	1.66	7,326

* Based on the data utilized, 3 % of the airframe surface area required no inspection in the timeframe under consideration

Based on the results presented, the net present value of an investment in a scheduled SHM system sized at optimum coverage ratio can be calculated, assuming weighted average cost of capital of 8 percent annually. The corresponding net present value over time is shown in Figure 14, assuming installation costs of 1,000 USD/m². It is clear that the overall profitability of the SHM investments, described in break-even time and total net present value, differs from the results presented in Table 4. As the net present value considers cost of capital and therefore adjusts future cash flows, the application of SHM to selected areas of the airframe possibly becomes more beneficial compared to instrumenting the entire airframe, as it requires only a smaller investment. The optimum airframe coverage ratio is therefore also a function of the cost of capital for the airline.

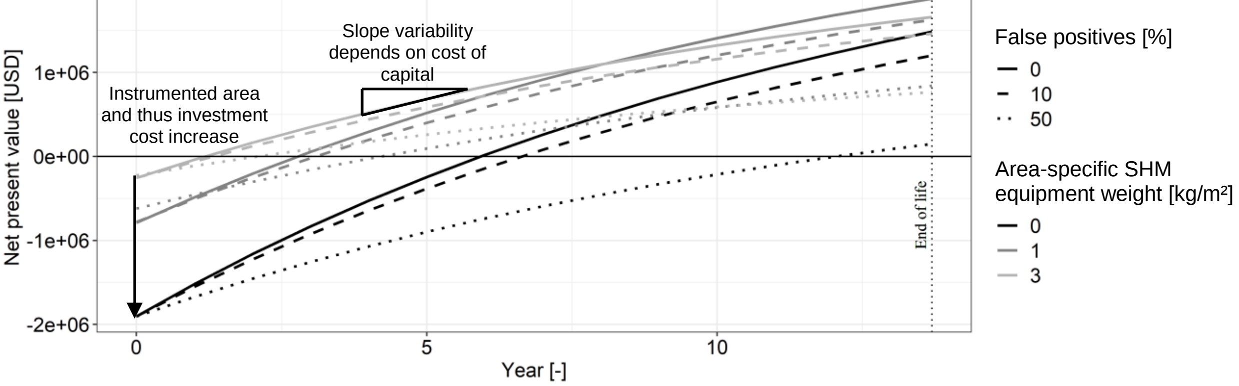


Figure 14 – Net present value of investment in scheduled SHM capabilities depending on system weight, performance and installation cost

4. Discussion

The work at hand presents the cost and benefit of dedicated SHM systems as a replacement for manual labor during scheduled aircraft inspections. Additionally, airframe design choices driven by inspectability are considered. Based on empirical data about the additional weight of structural cutouts, it is suggested that SHM can be used to achieve minor airframe weight improvements. However, more detailed information on load cases, geometry and expected damages is required to quantify the possible benefit. Based on the assumptions utilized, it is shown that SHM used during scheduled inspections can decrease the overall airframe inspection cost. Major influencing factors such as SHM system performance and its equipment weight, as well as installation cost, are considered. Depending on these factors, SHM systems can improve the overall financial efficiency of the aircraft by an amount that also renders scheduled SHM a beneficial investment for the airline, considering its cost of capital. However, the break-even period of a scheduled SHM system investment varies, depending on the coverage ratio. In this regard, this study proposes cost savings resulting from SHM as opposed to [12]. However, [12] assumed higher cost penalties due to reduced payload capacity, as the location of SHM equipment within the aircraft and its implications on payload capacity have been neglected. However, unlike [32], this study does not consider the maintenance processes themselves, neglecting the implications of SHM on the acceleration of the overall structural inspection process. Additionally, no damage types are considered, such as corrosion, fatigue or impact damage detection. As the monitoring technique utilized by the SHM system depends on the type of damage itself, it is possible that not all inspections required in the MPD are replaced with the same SHM system as assumed in this work, requiring further studies.

Treating SHM as general substitution for scheduled inspections, this paper provides indications about the system performance required to achieve a cash flow positive SHM system for an Airbus A320-like aircraft, expanding current studies by presenting a specific use case based on operational information. It has been emphasized that beneficial applications for scheduled SHM exist for airlines, depending on the performance of the SHM system. Furthermore, the results presented provide an indication of the required performance of a scheduled SHM system to become a viable investment opportunity for an airline. In future research, automated SHM can be investigated to improve scheduling of inspections.

5. Acknowledgements

We thank Dr. Kai-Daniel Büchter for reading earlier drafts and for his valuable feedback.

This research was funded by the Federal Ministry for Economic Affairs and Energy based on a decision by the German Bundestag in the national LuFo V program as a part of the research project Strubatex. The authors declare no conflict of interest.

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

6. Contact Author Email Address

dominik.steinweg@bauhaus-luftfahrt.net

7. Copyright Statement

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