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Cost–Benefit Analysis and Life Cycle Optimization of a Fibre Optic Structural Health Monitoring System for a Helicopter Rotor Blade

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Abstract. Structural Health Monitoring Systems (SHMS) enhance safety in aviation by enabling automated inspections; however, their adoption is often limited by concerns regarding lifecycle cost-effectiveness. This work investigates a composite sensorized helicopter tail rotor blade as a case study to evaluate the costs and benefits of a strain-based SHMS compared to a baseline "as-is" maintenance scenario. The maintenance strategy is optimized using an Ant Colony Optimization (ACO) algorithm, considering both Life Cycle Costs and safety constraints through a reliability model consistent with FAA regulations. Results indicate that, despite the additional cost of sensors, SHMS can provide economic benefits when combined with an appropriate maintenance strategy, while maintaining comparable safety levels in terms of Average Probability of Failure per Flight Hour (APFH). The optimal configurations correspond to a scheduled SHM approach, with frequent interrogations synchronized with other maintenance tasks, enabling extended Damage Inspection (DI) intervals while preserving General Visual Inspection (GVI) intervals. Moreover, the economic advantage of SHMS increases for more conservative maintenance strategies, with SHMS-based solutions outperforming the baseline in terms of Net Present Value (NPV) at similar APFH levels. These findings demonstrate the potential of SHMS to support cost-effective and safety-compliant maintenance strategies, even for components not typically considered ideal candidates for monitoring.

Keywords: cost-benefit analysis; maintenance optimization; fiber optic sensors; helicopter blade; reliability.

Variables' nomenclature

$n_{FBG} = number\ of\ FBG\ sensors\ to\ use\ in\ one\ blade$
$C_{FBG} = cost\ of\ one\ FBG\ sensor$
$L_{eng} = labour\ rate\ per\ engineer\ hour$
$L_{pilots} = labour\ rate\ of\ pilots$
$L_{tr\ wo} = labour\ rate\ per\ trained\ worker\ hour$
$n_{hel\ dep} = number\ of\ helicopters\ over\ which\ acquisition\ systems\ are\ depreciated$
$n_b = number\ of\ blades\ per\ helicopter\ (is\ equal\ to\ 4\ in\ this\ case)$
$c_{fuel} = cost\ of\ fuel\ per\ liter\ consumed\ by\ helicopter$
$q_{fuel} = quantity\ of\ fuel\ per\ hour\ consumed\ by\ helicopter\ from\ operational\ site\ to\ depot$
$t_{dep} = time\ for\ pilot\ to\ bring\ helicopter\ from\ site\ to\ depot$
$t_{mount\ blade} = time\ to\ mount\ all\ the\ rotor\ blades\ on\ the\ rotor\ hub$
$t_{GVI} = time\ to\ perform\ general\ visual\ inspection\ for\ all\ the\ rotor\ blades$

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t_{DI} = time to perform detailed inspection for all the rotor blades
t_{repair} = time to repair 1 blade
$c_{standard\ blade}$ = cost of the blade in without FBG's
$c_{blade\ with\ FBG's}$ = cost of the blade with FBG's
$K_{partition}$ = coefficient accounting for cost partitioning for blade maintenance
R = hourly revenue of the company per unit of helicopter
r = discount rate
d = damage size
T_f = time duration of one flight
ρ = pheromone evaporation rate
τ = pheromone intensity
η = desiderability
α = exponent of phermone intensity
β = exponent of desiderability
Superscript "as is" = cost element related to the "as is" scenario
Superscript "SHMS" = cost element attributed to the scenario "with SHMS"

Introduction

Structural Health Monitoring Systems (SHMS) have been extensively investigated in the literature over the past three decades. Their primary function is to provide information on the structural integrity of a system through integrated sensors and diagnostic techniques [1], as well as to estimate the Remaining Useful Life (RUL) using prognostic methodologies [2].
Compared to conventional Non-Destructive Techniques (NDT), SHMS offer significant advantages, as inspections can be performed in real time without disassembling structural components. This capability reduces downtime and minimizes maintenance costs associated with specialized labour.
Despite substantial research efforts—particularly in sensor integration strategies [3-5] and algorithmic approaches [6-8]—the industrial adoption of SHMS remains limited. Several factors contribute to this gap, including concerns about the reliability of damage detection performance, which must ensure an adequate Average Probability of Failure per Flight Hour (APFH) [9], as well as the overall costs associated with system implementation.
Indeed, notwithstanding their potential benefits, the economic impact of SHMS must be carefully assessed. In the aerospace field, the most significant cost drivers include the additional weight introduced by the system, which leads to increased fuel consumption, the intrinsic cost of the SHMS itself, and the consequences of false alarms, which may result in unnecessary aircraft grounding and associated downtime losses [10, 11].
The objective of this work is to optimize the economic benefits of an SHMS applied to a composite helicopter tail rotor blade equipped with fibre Bragg grating (FBG) sensors, while maintaining the safety standards prescribed by regulatory authorities.
This paper is structured as follows. Section 1 presents the application scenario of the SHMS along with the cost–benefit optimization methodology. Section 2 reports the results, and Section 3 provides the main conclusions.

1. Methodology

1.1 SHMS application scenarios

The application scenario of the SHMS considered in this work involves a composite helicopter tail rotor blade instrumented with FBG sensors. The helicopter is assumed to belong to a company that rents its fleet to operators in the Oil & Gas sector.
In this study, a Life Cycle Costing (LCC) approach is adopted. This methodology enables the comparison of different scenarios through selected performance indicators, in this case the Net Present Value (NPV).
Two scenarios are considered for comparison: the “as-is” scenario, representing the current operational condition without the implementation of SHMS, and the “with SHMS” scenario, in which

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the monitoring system is applied to the composite tail rotor blade. In both cases, the helicopter is assumed to have an operational lifetime of 30 years, with an average utilization of 500 flight hours (FH) per year.

The "as-is" scenario is assumed to be consistent with the one described in [12], and is briefly recalled here for clarity. Throughout its operational life, the blade undergoes periodic inspections to assess its structural integrity. Two types of inspections are performed: General Visual Inspection (GVI), conducted every 50 FH, and Detailed Inspection (DI), carried out every 1200 FH using a tap hammer, which requires removal of the blade from the tail rotor hub. The annual cash flows associated with the "as-is" scenario are reported in Eq. (1).

$$CF^{as\ is} = \sum_{i=1}^{n\ travels} 2At_{depot}K_{partition} + \sum_{i=1}^{n\ blade\ mount-sched} 2Bt_{mount\ blade} + \sum_{i=1}^{n\ blade\ mount-unsch} \frac{2}{n_b}Ct_{mount\ blade} + \sum_{i=1}^{n\ GVI} Bt_{GVI} + \sum_{i=1}^{n\ DI} Bt_{DI} + \sum_{i=1}^{n\ repairs} Ct_{repair-as\ is} + \sum_{i=1}^{n\ spare\ parts} c_{standard\ blade} \quad (1)$$

Where *A*, *B, and C* are defined according to Eq. (2).

$$A = \left(L_{pilots} + c_{fuel}q_{fuel} + R\right);\ B = \left(L_{tr\ wo} + RK_{partition}\right)\ and\ C = \left(L_{tr\ wo} + R\right) \quad (2)$$

The coefficient $K_{partition}$represents the ratio between the time required to perform maintenance on the blade and the time required to carry out maintenance on the entire helicopter. Several cost components contribute to the annual cash flow, including the cost of reaching the maintenance depot, the costs associated with blade installation and removal, the costs of performing GVI and DI, the repair costs, and the cost of blade replacement.

Scheduled maintenance activities are assumed to be performed concurrently with other maintenance operations; therefore, the associated revenue loss R is partitioned. In contrast, unscheduled maintenance activities are assumed not to be synchronized with other tasks; consequently, in these cases, R is not partitioned and $K_{partition}$is set equal to 1.

The "with SHMS" scenario, on the other hand, is not defined a priori. Instead, the Life Cycle Management (LCM) strategy for the helicopter blade is optimized according to the framework described in the following subsection. Nevertheless, the same maintenance activities as in the "as-is" scenario are considered, with the addition of automated inspections performed via the SHMS and interrogated by the operators. This leads to the formulation of Eq. (3), which is used to compute the annual cash flow.

$$CF^{with\ SHMS} = \sum_{i=1}^{n\ travels-sched} 2At_{depot}K_{partition} + \sum_{i=1}^{n\ travels-unsch} 2At_{depot} + \sum_{i=1}^{n\ blade\ mount-sched} 2Bt_{mount\ blade} + \sum_{i=1}^{n\ blade\ mount-unsch} \frac{2}{n_b}Ct_{mount\ blade} + \sum_{i=1}^{n\ GVI-sched} Bt_{GVI} + \sum_{i=1}^{n\ GVI-unsch} \frac{1}{n_b}Ct_{GVI} + \sum_{i=1}^{n\ DI-sched} Bt_{DI} + \sum_{i=1}^{n\ DI-unsch} \frac{1}{n_b}Ct_{DI} + \sum_{i=1}^{n\ repairs} Ct_{repair-with\ SHMS} + \sum_{i=1}^{n\ spare\ parts} c_{blade\ with\ FBGs} \quad (3)$$

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In addition to the cost model previously described, a reliability model is incorporated in order to integrate the economic analysis with safety constraints. The same reliability framework presented in [12] is adopted and is briefly summarized here for completeness.
The cost models defined in Eq. (1) and Eq. (3) are implemented within a computational framework performing Probabilistic Damage Tolerance Analysis (PDTA). An average of one impact event on the tail rotor blade is assumed every 1000 FH, resulting in a total of 15 impact events over the entire operational life of the helicopter. These events are modelled using a Poisson discrete distribution for each PDTA simulation run.
The impact energy is assumed to follow a Weibull distribution, while the resulting damage characteristics—namely residual indentation, surface damage dimensions, and skin–foam disbonding as functions of impact energy—are modelled according to the relationships reported in [12]. Fig 1a illustrates the cross-section of the blade.
The degradation of residual strength is estimated as a function of the ratio between the residual core area after indentation and the initial core area, as defined in Eq. (4). The parameter $k_{\text{concentration}}$represents a stress concentration factor and is assumed equal to 1.5.

$$strength\ ratio = 1 - k_{concentration}\frac{indentation\ area}{core\ area} \tag{4}$$

The indentation area is calculated according to Eq. (5).

$$indentation\ area = 2\int_0^{indentation} \sqrt{4.7 \times\ chordwise\ coordinate} = 2.89 \times indentation^{3/2} \tag{5}$$

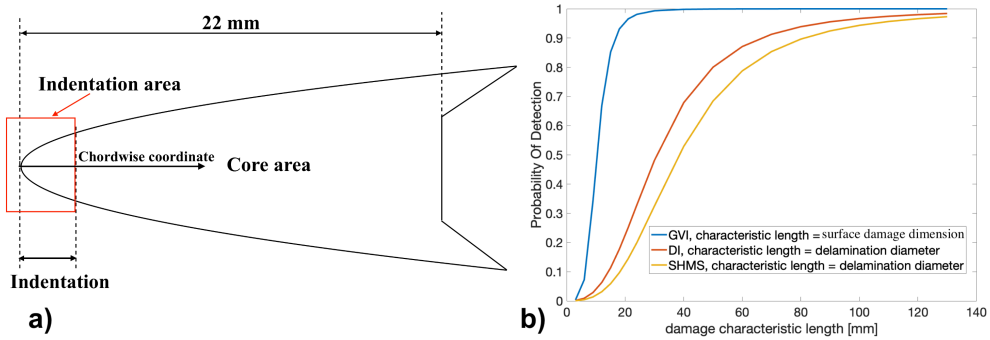

Fig 1: a) cross-section of the blade core, adapted from; b) Probability Of Detection (POD) curves for GVI and DI, adapted from, and SHMS POD curve having a Probability of False Alarm of 0.12%. Image adapted from [12].

Fig 1b presents the Probability of Detection (POD) curves adopted in this study. The curves corresponding to GVI and DI are taken from [12]. The DI and SHMS POD curves are expressed as functions of the delamination size, whereas the GVI curve is defined as a function of the surface damage dimension. The POD curve associated with the SHMS is derived from [8] and exhibits lower detection performance compared to DI. A Probability of False Alarm (PFA) of 0.12% is assumed, corresponding to a configuration with 200 FBG sensors.
The load exceedance probability is adopted from [12], and the Probability of Failure (POF) of the blade is subsequently evaluated by considering consecutive time intervals in series. The initial blade strength ratio is assumed equal to 1.78, representing the ratio between the failure load and the limit load. The value of the APFH was calculated in accordance with the FAA Advisory Circular [9], and the operational life of the blade was simulated hour-by-hour for 30000 times to reach the convergence. The APFH was calculated according to Eq. (6).

$$APFH = \frac{P_{per\ flight}}{T_f}$$

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(6)

Where the failure probability per flight $P_{per\ flight}$ was calculated as in Eq. (7).

$$P_{per\ flight} = \frac{1}{N}\sum_{k=1}^{N} P_{k-th\ flight} \tag{7}$$

And the failure probability in the k-th flight $P_{k-th\ flight}$ was calculated as in Eq. (8) by combining the prior failure probability P_{prior} and the failure probability during flight $P_{during\ flight}$.

$$P_{k-th\ flight} = P_{prior} + (1 - P_{prior}) \times P_{during\ flight} \tag{8}$$

The values of the variables reported in Table 1 are adopted throughout the analysis. It is further assumed that, in the "with SHMS" scenario, the time required to perform an unscheduled DI and GVI is 20% of that required under scheduled conditions. This assumption is justified by the capability of the SHMS to localize damage, thereby facilitating and accelerating the inspection process.

Table 1: values assumed for the variables

Variable	Value
C_{FBG}	30 €
r	8.6%
L_{pilots} and $L_{tr\ wo}$	48.2 €/h and 28 €/h
c_{fuel} and q_{fuel}	0.48 €/l and 568 l/h
$c_{blade}^{as\ is}$	40000 €
R	6560.6 €/h
$t_{mount\ blade}$	0.5 h
t_{DI} and t_{GVI}	15 h and 0.652 h
$t_{repair\ as\ is}$	8 h

1.2 Optimization framework for the scenario "with SHMS"

In this work, an optimization was performed to understand the most suitable maintenance process compatible with the SHMS application scenario. More in specific, the Ant Colony Optimization (ACO) algorithm [13] was applied. Such choice was made since ACO works particularly well in solving discrete optimization problems. The algorithm works similarly to the way the ants seek their path in a colony. At each iteration, a family of artificial ants is let going through multiple paths, and, at the end of each iteration, each ant releases a quantity of pheromone proportional to the quality of the path, that is represented in this case by the value of the fitness function. The pheromone released on the path evaporates at each iteration, consistently to what was observed in nature, and this helps the algorithm in avoiding local minima. The code reaches the convergence when no significant improvement of the fitness function is obtained throughout the iterations.
The fitness function is represented by the PDTA code, which simulates hour-by-hour the operational life of the blade integrating the cost and reliability model, and provides in output the value of the NPV and the APFH. A penalty on the value was added to the NPV, proportional to the absolute value of the difference between the APFH in the scenario "as-is", and the value obtained during the optimization. In such a way it is possible to compare the two scenarios for a similar value of APFH.
At each iteration, the candidate solution is encoded into a list of parameters in input to the code, which is represented by the indexes of each vector. The following variables, contained into vectors from x_1 to x_7, were considered in the optimization:

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$$\begin{cases} x_1 = DI\ interval\ \in \{300, 600, .., 6000\}\ FH \\ x_2 = GVI\ interval\ \in \{10, 20, \dots, 100\}\ FH \\ x_3 = SHMS\ interval\ \in \{1, 1000, 2000, \dots., 10000\}\ FH \\ x_4 = GVI\ scheduled \in \{0,1\} \\ x_5 = DI\ scheduled\ \in \{0,1\} \\ x_6 = SYNC\ \in \{0,1\} \\ x_7 = SHMS\ SYNC\ coefficient\ \in \{1,2,\dots,10\} \end{cases}$$

Where x_1 represents the vector containing DI intervals, x_2 represents the vector containing GVI intervals, x_3 represents the vector containing SHMS automatic inspection intervals, x_4, x_5, and x_6 represents Boolean vectors providing the code with the information of whether performing or not scheduled GVI, DI, and synchronization between global maintenance activity performed on the helicopter every 300 FH, and the SHMS interrogation. Eventually, the vector x_7 contains a set of coefficients multiplying the general helicopter maintenance interval of 300 FH to define the SHMS inspection interval.
The probability for each k-th ant, positioned on one vector's element x, to move towards one of the elements of the next vector y is calculated according to Eq. (9).

$$p_{xy}^k = \frac{\tau_{xy}^\alpha \eta_{xy}^\beta}{\sum_y \tau_{xy}^\alpha \eta_{xy}^\beta} \tag{9}$$

Where τ_{xy} is the amount of pheromone deposited in the transition from x to y, η_{xy} is the desiderability of state transition from x to y, in this work assumed equal to 1. α was set equal to 2.5, and represents the parameter to control the influence of the amount of pheromone, and, analogously, η represents the parameter to control the influence of the desiderability, which in this case was not influent being equal to 1. The pheromone is updated twice within each iteration: one in each transition from x to y, called local updating, and the other after each iteration, called global updating. The updating rules are presented in Eq. (10).

$$\begin{cases} \tau_{xy} \leftarrow (1 - \rho_{local})\tau_{xy} + \rho_{local}\tau_0 & local\ updating \\ \tau_{xy} \leftarrow (1 - \rho_{global})\tau_{xy} + \rho_{global}\Delta\tau_{xy} & global\ updating \end{cases} \tag{10}$$

Where τ_0 represents the initial pheromone intensity, set equal to 0.5, ρ represents the pheromone's evaporation rate, chosen equal to 0.1, $\Delta\tau_{xy}$ represents the amount of pheromone deposited by the k-th ant, which is equal to quantity Q/L_k, where L_k represents the value of the fitness function, and Q is a constant set equal to 2 if the k-th ant follows the x to y path, 0 otherwise. Given the probability p_{xy}^k, the next vector's element y is chosen with two different methods, in accordance with the decision theory: exploration and exploitation. In exploitation, the element y is chosen based on the higher value of p_{xy}^k, while in exploration, the selection of y is made based on the roulette wheel selection methodology. The choice among the two methods is made randomly by sampling from a uniform distribution a value Q_m between 0 and 1. If the value results higher than the threshold Q_m^0, then exploitation is selected, otherwise exploration. Q_m^0, was varied introducing a dynamic annealing schedule [14], varying the parameter throughout the optimization, from 0.75 to 0.95, at the beginning and the end, respectively. The optimization algorithm was run with a total of 50 ants and 40 iterations.

2. Results

Before executing the optimization procedure for the "with SHMS" scenario, the NPV was first evaluated for the baseline "as-is" configuration, adopting the maintenance policy described in Subsection 1.1. This preliminary assessment provides a reference for comparison with the SHMS-

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enabled scenario. The results yield an APFH equal to $APFH^{\text{as is}} = 7.64 \times 10^{-10}$, with a corresponding NPV of $NPV_{\text{ref}} = 189046\,€$. This value is therefore used as the benchmark for subsequent analyses involving the SHMS scenario. Fig. 2a illustrates the Probability of Failure as a function of FH over the helicopter's operational lifetime. In accordance with the definition provided by the FAA [9], the average APFH is computed by first averaging the Probability of Failure across multiple flights, as expressed in Eq. (7), and subsequently normalizing this value by the mean flight duration. In the present study, the average flight duration is assumed to be 1 hour (see Eq. (6)).

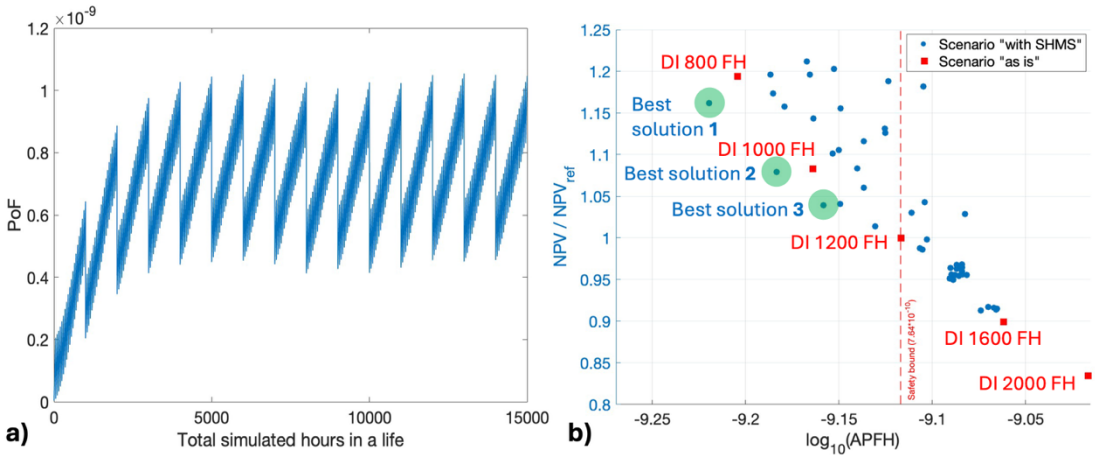

Fig 2: a) Probability Of Failure during the Flight Hours; b) Comparison between "as-is" and "with SHMS" scenarios in the Net Present Value - Average Probability of Failure per Flight Hour domain.

Fig. 2b presents the optimization results for the "with SHMS" scenario (blue markers), alongside the baseline "as-is" solution, indicated by the vertical red dashed line. The y-axis represents the ratio between the NPV of each solution and the reference value NPV_{ref}. Due to the discrete nature of the problem and the inclusion of a penalty term on the APFH, it was not possible to identify solutions with identical APFH values across the two scenarios. Instead, a set of optimal and near-optimal solutions was obtained for the "with SHMS" scenario, corresponding to different APFH levels. In addition, a sensitivity analysis was conducted for the "as-is" scenario to enable a meaningful comparison with the SHMS-enabled solutions. This analysis considered different DI intervals, specifically 800, 1000, 1600, and 2000 FH. The resulting solutions are shown in Fig. 2b as red squares. A comparison between the two scenarios indicates that, at higher APFH values (to the right of the vertical dashed line), their performance is broadly comparable. Conversely, for lower APFH values (i.e., safer solutions), the "with SHMS" scenario demonstrates superior performance, yielding lower NPV values for similar APFH levels. These solutions, labelled as Best Solution 1, 2, and 3 in Fig. 2b, highlight the benefits of SHMS integration. Notably, all the best-performing solutions that outperform the "as-is" scenario include both scheduled DI and GVI tasks. These solutions are characterized by extended DI intervals (greater than 1800 FH), while maintaining GVI intervals comparable to the baseline value of 50 FH. Furthermore, all optimal configurations involve synchronization between SHMS interrogation activities and other scheduled maintenance tasks, resulting in relatively short SHMS interrogation intervals (below 900 FH). Detailed information on these solutions is provided in Table 2.

Table 2: maintenance plan features of the best solutions found in the optimization.

Best solution	DI interval	GVI interval	SHMS interval	GVI scheduled	DI scheduled	SYNC	SYNC coefficient
1	5400	40	600	1	1	1	2
2	2400	70	300	1	1	1	1
3	1800	30	900	1	1	1	3

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3. Conclusions

In this work, an optimal maintenance strategy for composite, sensorized helicopter tail rotor blades was identified using an ACO algorithm. The objective was to minimize life-cycle costs while satisfying safety constraints imposed by aviation regulations, evaluated in terms of APFH and NPV. Notably, the algorithm selected a scheduled SHM configuration rather than a continuous (online) approach, as indicated by an SHMS interrogation interval greater than 1 FH. Moreover, SHMS interrogations should be performed at relatively short intervals and synchronized with other scheduled maintenance tasks to reduce overall system downtime. The optimal solution suggests adopting relatively long DI intervals, while GVI intervals remain consistent with the "as-is" maintenance policy. It is also worth noting that, based on the observed trends, the economic benefits associated with SHMS implementation tend to increase for more conservative (i.e., safer) maintenance strategies. Overall, although rotor blades are typically not considered ideal candidates for SHMS from an economic perspective, since the greatest benefits are generally associated with components requiring disassembly for inspection and that rarely exhibit damage, the present study demonstrates that a cost-effective and safety-compliant maintenance strategy can still be achieved. In particular, an SHMS-enabled approach was found to outperform the existing maintenance plan even for a component traditionally regarded as unsuitable for cost-effective monitoring.

References

[1] Farrar, C. R., & Worden, K. (2007). An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1851), 303-315.
[2] Farrar, C. R., & Lieven, N. A. (2007). Damage prognosis: the future of structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1851), 623-632.
[3] Airoldi, A., Ballarin, P., Di Mauro, S., Rigamonti, D., Reinert, F., Dadras, M. M., ... & Cartabia, L. (2023). Development of an additive manufactured fitting sensorized with optical fibres for load recognition. In *AIAA Scitech 2023 forum* (p. 2079).
[4] Sala, G., Di Landro, L., Airoldi, A., & Bettini, P. (2015). Fibre optics health monitoring for aeronautical applications. *Meccanica*, *50*(10), 2547-2567.
[5] Airoldi, A., Ballarin, P., Di Mauro, S., Bettini, P., Rigamonti, D., De Nicolò, E., & Dadras, M. (2025). Turning aeronautical brackets into smart monitoring devices: integration of sensors and load identification algorithms. *Structural Health Monitoring*, 14759217251404360.
[6] Sbarufatti, C., Manes, A., & Giglio, M. (2013). Performance optimization of a diagnostic system based upon a simulated strain field for fatigue damage characterization. *Mechanical Systems and Signal Processing*, *40*(2), 667-690.
[7] Galanopoulos, G., Eleftheroglou, N., Milanoski, D., Broer, A., Zarouchas, D., & Loutas, T. (2023). A novel strain-based health indicator for the remaining useful life estimation of degrading composite structures. *Composite Structures*, *306*, 116579.
[8] Ballarin, P., Sala, G., Macchi, M., Roda, I., Baldi, A., & Airoldi, A. (2024). Application of artificial neural networks to a model of a helicopter rotor blade for damage identification in realistic load conditions. *Sensors*, *24*(16), 5411.
[9] AC 25.1309-1B: System design and analysis. Advisory circular, Federal Aviation Ad- ministration, U.S. Department of Transportation, 2024.
[10] Dong, T., & Kim, N. H. (2018). Cost-effectiveness of structural health monitoring in fuselage maintenance of the civil aviation industry. *Aerospace*, *5*(3), 87.
[11] Cusati, V., Corcione, S., & Memmolo, V. (2021). Impact of structural health monitoring on aircraft operating costs by multidisciplinary analysis. *Sensors*, *21*(20), 6938.
[12] Ballarin, P., Macchi, M., Roda, I., Sala, G., Baldi, A., & Airoldi, A. (2024). Economic Impact Assessment of Structural Health Monitoring Systems on the Lifecycle of a Helicopter Blade. *THE E-JOURNAL OF NONDESTRUCTIVE TESTING*, *29*(7), 1-8.
[13] Dorigo, M., Birattari, M., & Stutzle, T. (2006). Ant colony optimization. *IEEE computational intelligence magazine*, *1*(4), 28-39.
[14] Qing Zhang, Felix T. S. Chan, and Xiaowen Fu. Improved ant colony optimization for the operational aircraft maintenance routing problem with cruise speed control. Journal of Advanced Transportation, 2023:1–18, 2023. doi: 10.1155/2023/8390619.

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