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Economic Impact Assessment of Structural Health Monitoring Systems on the Lifecycle of a Helicopter Blade

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Abstract. Structural Health Monitoring Systems (SHMS) are widely investigated in the literature, however, their application in the aerospace industry is still limited. One of the reasons lies in the lack of methods evaluating their economic impact on the lifecycle of the structures. In this work, the economic impact of a Fibre Bragg Grating (FBG)-based SHMS is assessed on a composite helicopter tail rotor blade, considering two perspectives: Beginning Of Life (BOL), and Middle Of Life (MOL). Two scenarios are compared according to the Life Cycle Costing methodology: the current one, and the one including the SHMS. In the BOL, the FBG's replace the thermocouples, adopted for the development of the curing cycle; while during the blade certification tests, the FBG's replace the strain gauges. In the MOL the SHMS performs automatic scheduled inspections of the tail rotor blade. The lifecycle of the helicopter is implemented in the Probabilistic Damage Tolerance Analysis to compare two scenarios having the same blade Probability Of Failure. The detection performance and false alarms of the SHMS are considered. Results show that an economic benefit may be achieved using the SHMS in the development of a new blade, potentially reducing the number of blade tested and the number of autoclave curing cycles. Moreover, the scheduled detailed inspection interval can be extended if automatic SHMS inspections are performed in addition to it, maintaining the same Probability Of Failure. However, due to the frequent impacts with foreign objects, the repair complexity of a sensorized structure, and its higher cost compared to a standard blade, the economic impact of the SHMS is evaluated as negative on the lifecycle of the blade.

Keywords: Life Cycle Costing ; Structural Health Monitoring ; Fibre Bragg Grating sensor; manufacturing ; maintenance

Nomenclature

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n_{auto} = number of autoclave curing cycles
n_{test} = number of blade tested in laboratory
C_m = cost of prepreg material
t_{lam} = time for lamination of the blade
$t_{em\ FBG}$ = time to embed one FBG sensor
n_{FBG} = number of FBG sensors to use in one blade
$t_{em\ th}$ = time to embed one thermocouple or to apply one thermocouple on mould
n_{th} = number of thermocouples embedded or applied to monitor temperature during curing cycle
C_{en} = cost per unit of time of energy for autoclave curing cycle
t_{auto} = time to polymerize one blade in autoclave
$C_{acq\ sys}$ = cost of one acquisition system
$C_{FBG\ sys}$ = cost of one FBG interrogation system
C_{FBG} = cost of one FBG sensor
$t_{ev\ th}$ = time to evaluate thermocouple data quality
$t_{ev\ FBG}$ = time to evaluate FBG data quality
L_{eng} = labour rate per engineer hour
L_{pilots} = labour rate of pilots
C_{th} = cost of one thermocouple
$L_{tr\ wo}$ = labour rate per trained worker hour
n_g = number of strain gauges applied to one blade
C_g = cost of one strain gauge
t_g = time to apply one strain gauge
$t_{t\ b}$ = time to test one blade in laboratory
$t_{ev\ g}$ = time to evaluate strain gauge data quality obtained during blade testing
$n_{hel\ dep}$ = number of helicopters over which acquisition systems are depreciated
n_b = number of blades per helicopter (is equal to 4 in our case)
t_{bag} = time to prepare vacuum bag
t_{mould} = time to prepare the mould
$t_{demould}$ = time to remove blade from mould
m_{blade} = mass of the blade
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
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
Apex "as is" = cost element related to the "as is" scenario
Apex "SHMS" = cost element attributed to the scenario "with SHMS"

1. Introduction

Although in the literature the performances of Structural Health Monitoring Systems (SHMS) were widely investigated [1-3], their application in aviation is still limited. One of the reasons lies in the lack of methods assessing their economic impact on the monitored structures. Some works were presented in the literature regarding the assessment of the cost-effectiveness of such systems. For instance in [4] the authors investigated the economic impact of a piezoelectric-based SHMS on the fuselage of a Boeing 737, and they concluded that the additional weight given by the SHMS would have reduced the number of passengers and increased the fuel consumption. In [5] the authors assumed an increase in the design allowable stresses thanks to the presence of the SHMS, and they concluded that a weight reduction of the structure equal to 5% could be achieved, and consequently, a saving in the consumed fuel would be obtained. In [6], the authors investigated the effects of the usage of a SHMS on an Airbus A220, and they concluded that the weight increase coming from the

SHMS would have led to a decrease of the aircraft performance, leading to a negative economic impact of the SHMS. In [7] the authors assessed the economic impact of a SHMS based on piezoelectric and Fibre Bragg Grating (FBG) sensors applied on an Airbus A320, and they concluded that an economic benefit would be achieved by using the SHMS for the Detailed Visual Inspection (DVI) and the General Visual Inspection (GVI) operations.

The studies presented in the literature focused on aircraft, and they considered only the usage phase of the aircraft, neglecting the effects and the potential benefit, that a SHMS may have on the production and development of new aeronautical structures. In this work, the economic impact assessment of a FBG-based SHMS is investigated on a composite helicopter tail rotor blade following two perspectives: Beginning Of Life (BOL), corresponding to the development of a new composite blade, and Middle Of Life (MOL), corresponding to the usage and maintenance of the composite tail rotor blade.

This work is structured as it follows. In section 2, the application scenarios are presented, and the cost model is derived following the Life Cycle Costing (LCC) methodology. In section 3, the results are presented considering both the BOL and the MOL perspectives, and highlighting the trade-off between maintenance cost and safety. In section 4, the conclusions and the main findings are discussed.

2. Scenarios description and cost model derivation

The LCC methodology allows comparing different scenarios with the goal to identify which is the most suitable to achieve a predefined objective. Therefore, two alternative scenarios are compared: the current one, hereafter named “as is” scenario, and the one adopting the SHMS, hereafter named scenario “with SHMS”. The two scenarios are compared under the two perspectives of BOL and MOL.

2.1 Beginning Of Life

The development of a new composite blade require the accomplishment of two steps: development of the curing cycle and execution of mechanical tests performed in laboratory to assess the mechanical properties.

Develop a curing cycle means finding the proper temperature and pressure distribution over time such to obtain the desired mechanical properties of the final laminate. This operation is currently carried out performing different curing cycles and measuring the temperature distribution inside the material through the embedded thermocouples. The curing cycle is repeated adjusting the cycle parameters until the desired temperature is read by the thermocouples. In the scenario “with SHMS”, the FBG sensors are supposed providing the temperature field during the curing cycle, replacing the thermocouples. Due to their low invasiveness and their immunity to the electromagnetic disturbances, FBG sensors are supposed exhibiting a higher quality in the measure of the temperature field compared to the thermocouples. This aspect could lead to a saving in the number of curing cycles needed to find the proper curing parameters. It must be remarked that at each curing cycle, a new blade must be produced and scraped at the end of the cycle. The cost model to develop the curing cycle for a new composite blade is presented in Eq. (1) and in Eq. (2) for the scenario “as is” and “with SHMS” respectively.

$$\begin{aligned} & C_{cur\ cycle\ def}^{as\ is} \\ &= \left(C_m m_{blade} + L_{tr\ wo}\left(t_{lam} + t_{em\ th} n_{th} + t_{bag} + t_{mould} + t_{demould}\right) + n_{th} C_{th} + C_{en} t_{auto} + t_{ev\ th} L_{eng}\right) n_{auto}^{as\ is} \\ &+ C_{acq\ sys} \frac{t_{auto} n_{auto}^{as\ is}}{t_{auto} n_{auto}^{as\ is} + t_{t\ b} n_{test}^{as\ is}} \end{aligned} \tag{1}$$

$$\begin{aligned}&C^{SHMS}_{cur\ cycle\ def}\\&= \Big(C_m m_{blade} + L_{tr\ wo}\big(t_{lam} + t_{em\ FBG} n_{FBG} + t_{bag} + t_{mould} + t_{demould}\big) + C_{FBG} n_{FBG} + C_{en} t_{auto}\\&+ L_{eng} t_{ev\ FBG}\Big) n^{SHMS}_{auto} + C_{FBG\ sys} \frac{t_{auto} n^{SHMS}_{auto}}{t_{auto} n^{SHMS}_{auto} + t_{t\ b} n^{SHMS}_{test}}\end{aligned} \tag{2}$$

The next step consists in the accomplishment of mechanical tests performed in laboratory: this is currently done applying different load conditions to the blade in a test fixture and measuring the strain values using the strain gauges. In this phase, the SHMS is supposed replacing the strain gauges with the FBG sensors embedded in the blade during the manufacturing. A higher quality in the measurement of the FBG sensors is expected compared to the strain gauges. Therefore, a lower number of mechanical tests could be required. The cost models for the mechanical tests are presented in Eq. (3) and Eq. (4) for the scenario "as is" and "with SHMS", respectively.

$$\begin{aligned}&C^{as\ is}_{test\ lab}\\&= \Big(C_m m_{blade} + L_{tr\ wo}\big(t_{lam} + t_{em\ th} n_{th} + t_{bag} + t_{mould} + t_{demould} + t_g n_g\big) + C_{en} t_{auto} + C_g n_g\\&+ L_{eng}\big(t_{t\ b} + t_{ev\ g}\big)\Big) n^{as\ is}_{test} + C_{th} n_{th} + C_{acq\ sys} \frac{t_{t\ b} n^{as\ is}_{test}}{t_{auto} n^{as\ is}_{auto} + t_{t\ b} n^{as\ is}_{test}}\end{aligned} \tag{3}$$

$$\begin{aligned}&C^{SHMS}_{test\ lab}\\&= \Big(C_m m_{blade} + L_{tr\ wo}\big(t_{lam} + t_{em\ FBG} n_{FBG} + t_{bag} + t_{mould} + t_{demould}\big) + C_{FBG} n_{FBG} + L_{eng}\big(t_{t\ b} + t_{ev\ FBG}\big)\\&+ C_{en} t_{auto}\Big) n^{SHMS}_{test} + C_{FBG\ sys} \frac{t_{t\ b} n^{SHMS}_{test}}{t_{auto} n^{SHMS}_{auto} + t_{t\ b} n^{SHMS}_{test}}\end{aligned} \tag{4}$$

2.2 Middle Of Life

During the operational life, the blade is subjected to periodical inspections to assess its state of integrity. In the scenario "as is" two types of inspections are performed: General Visual Inspection (GVI), performed every 50 Flight Hours (FH) and Detailed Inspection (DI), performed every 1200 FH with a tap hammer, removing the blade from the tail rotor hub. In the scenario "with SHMS", the helicopter changes its maintenance policy during the years. In the first 10 years, DI is performed every 2400 FH, and automatic inspections are performed in addition, interrogating the SHMS at scheduled intervals with the helicopter on ground. In the next 10 years the blade is dismounted from the tail rotor hub 50% of the DIs. In the last 10 years, DI is replaced by the scheduled automatic inspection performed with the SHMS. GVI is performed at the same way as in the scenario "as is". The annual Cash Flows are presented in Eq. (5) and Eq. (6) for the scenario "as is" and "with SHMS" respectively.

$$\begin{aligned}&CF^{as\ is}\\&= \sum_{i=1}^{n\ travels} 2At_{depot} K_{partition} + \sum_{i=1}^{n\ blade\ mount-sched} 2Bt_{mount\ blade} + \sum_{i=1}^{n\ blade\ mount-unsch} \frac{2}{n_b} Ct_{mount\ blade} + \sum_{i=1}^{n\ GVI} Bt_{GVI}\\&+ \sum_{i=1}^{n\ DI} Bt_{DI} + \sum_{i=1}^{n\ repairs} Ct_{repair-as\ is} + \sum_{i=1}^{n\ spare\ parts} c_{standard\ blade}\end{aligned} \tag{5}$$

$$
\begin{aligned}
CF^{with\ SHMS} &= \sum_{i=1}^{n\ travels-sched} 2At_{depot}K_{partition} + \sum_{i=1}^{n\ travels-unsch} 2At_{depot} \\
&+ \sum_{i=1}^{n\ blade\ mount-sched} 2Bt_{mount\ blade} + \sum_{i=1}^{n\ blade\ mount-unsch} \frac{2}{n_b}Ct_{mount\ blade} + \sum_{i=1}^{n\ GVI-sched} Bt_{GVI} + \sum_{i=1}^{n\ GVI-unsch} \frac{1}{n_b}Ct_{GVI} \\
&+ \sum_{i=1}^{n\ DI-sched} Bt_{DI} + \sum_{i=1}^{n\ DI-unsch} \frac{1}{n_b}Ct_{DI} + \sum_{i=1}^{n\ repairs} Ct_{repair-with\ SHMS} + \sum_{i=1}^{n\ spare\ parts} c_{blade\ with\ FBG's}
\end{aligned} \tag{6}
$$

Where A, B, *and* C are defined according to Eq. (7).

$$
A = \left(L_{pilots} + c_{fuel}q_{fuel} + R\right); B = \left(L_{tr\ wo} + RK_{partition}\right)\ and\ C = \left(L_{tr\ wo} + R\right) \tag{7}
$$

The coefficient $K_{partition}$ is the ratio between the time to perform the maintenance on the blade and the time to perform the maintenance on the whole helicopter. Different terms contribute to the annual cash flow in the two scenarios: the cost to reach the depot, the cost to mount/dismount the blade, the cost to perform GVI and DI, the cost to repair the blade and the cost of the blade spare part. Scheduled activities are supposed to be performed together with other maintenance tasks, therefore the revenue loss R is partitioned, while the unscheduled activities are supposed not to be synchronized with other tasks, therefore, in this case R is not partitioned, and $K_{partition}$ is set equal to 1. The cost models in Eq. (5) and Eq. (6) are implemented in a code performing the Probabilistic Damage Tolerance Analysis (PDTA) [8]. According to [9], a helicopter main rotor is subjected to 1 impact event every 1000 FH in marine environment: we will assume this data also for the tail rotor. Considering an average of 500 FH per year, for 30 years of life, 15 impact events are supposed to occur during the whole life of the helicopter, which are distributed according to a Poisson discrete distribution for each run of PDTA. The impact energies are distributed according to a Weibull, as presented in [10], considering a “medium energy”. The residual indentation, the surface damage dimension and the skin-foam disbonding versus the impact energy of the blade follows the behaviour presented in [11]. Figure 1a represents the cross section of the blade: the residual strength degradation is estimated function of the ratio between the residual core area after the indentation and the initial core area, according to Eq. (8), where the parameter $k_{concentration}$ represents a stress concentration factor, assumed equal to 1.5.

$$
strength\ ratio = 1 - k_{concentration}\frac{indentation\ area}{core\ area} \tag{8}
$$

The indentation area is calculated according to Eq. (9).

$$
indentation\ area = 2\int_{0}^{indentation} \sqrt{4.7 \times\ chordwise\ coordinate} = 2.89 \times indentation^{3/2} \tag{9}
$$

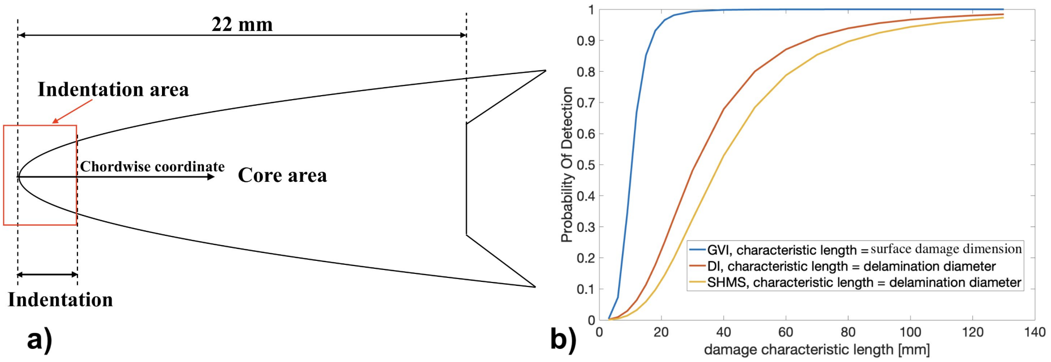

Figure 1: a) cross-section of the blade core, adapted from [11]; b) Probability Of Detection (POD) curves for GVI and DI, adapted from [12], and SHMS POD curve having a Probability of False Alarm of 0.12%.

Figure 1b shows the POD curves adopted in this work, the curves for the GVI and for the DI are the ones presented in [12]. The DI and SHMS curves are plotted versus the delamination dimension, while the GVI curve is plotted versus the surface damage dimension. The POD curve of the SHMS is supposed showing lower performances compared to the DI, and a Probability of False Alarm (PFA) of 0.12% is considered, obtained with 450 FBG sensors. The load exceedance probability is the one presented in [13], and the Probability Of Failure (POF) of the blade is then computed considering each time interval in series with the following. The initial blade strength ratio is 2, representing the ratio between the failure load and the Limit Loads.

3. Results

The following values presented in Table 1 are assumed for the variables.

Table 1: values assumed for the variables

Variable	Value
C_{FBG}, C_g, and C_{th}	90 €, 1 €, and 10 €
C_m and C_{en}	181.56 €/kg and 10.6 €/h
$C_{FBG\ sys}$ and $C_{acq\ sys}$	20000 € and 13000 €
$t_{em\ FBG}$ and t_g	0.083 h and 0.333 h
t_{lam} and t_{auto}	24 h and 8 h
$t_{em\ th} = t_{ev\ th} = t_{ev\ FBG} = t_{ev\ g}$	0.0167 h
$t_{int\ b}$	0.125 h
t_{bag}	0.333 h
t_{mould} and $t_{demould}$	0.25 h and 0.0833 h
$t_{t\ b}$	40 h
r	8.6%
L_{pilots}, $L_{tr\ wo}$ and L_{eng}	48.2 €/h, 28 €/h, and 42 €/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

3.1 Beginning Of Life

The results are presented in Figure 2, where the differential costs between the two scenarios “as is” and “with SHMS” are presented.

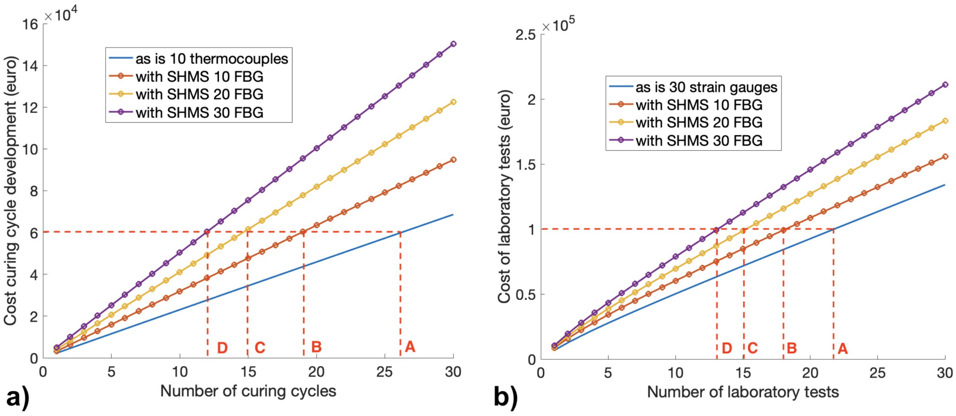

Figure 2: a) differential cost of curing cycle development in the two scenarios for a cost of 60k€; b) differential cost of mechanical laboratory tests in the two scenarios for a cost of 100k€

Referring to Figure 2a, and considering a cost of 60 k€, the corresponding number of curing cycles for the scenario "as is" is equal to 26 (point A). Considering the scenario "with SHMS", the same cost corresponds to a number of curing cycles equal to 13, 15, and 19 (points D, C, and B), using 30, 20, and 10 FBG sensors respectively. However, if the increase in the accuracy of the temperature field obtained with the FBG sensors allows reducing the number of curing cycles below 13, 15, and 19, using 30, 20, and 10 FBG sensors respectively, the scenario "with SHMS" starts providing economic benefits. An analogous result can be observed in the laboratory tests for the blade certification, in Figure 2b. Considering a cost of 100 k€, if the increase in the accuracy of the strain field allows reducing the number of laboratory tests from 23, in the scenario "as is" (point A), below 13, 15, and 18, (points D, C, and B), using 30, 20, and 10 FBG sensors respectively, then an economic benefit can be achieved adopting the SHMS.

3.2 Middle Of Life

Results are presented in Figure 3, where the POF and the Net Present Value (NPV) are plotted versus the inspection interval of the SHMS. The NPV of the two scenarios are compared at the same POF equal to 8.43×10^{-10}, obtained for a SHMS inspection interval equal to 1070 FH.

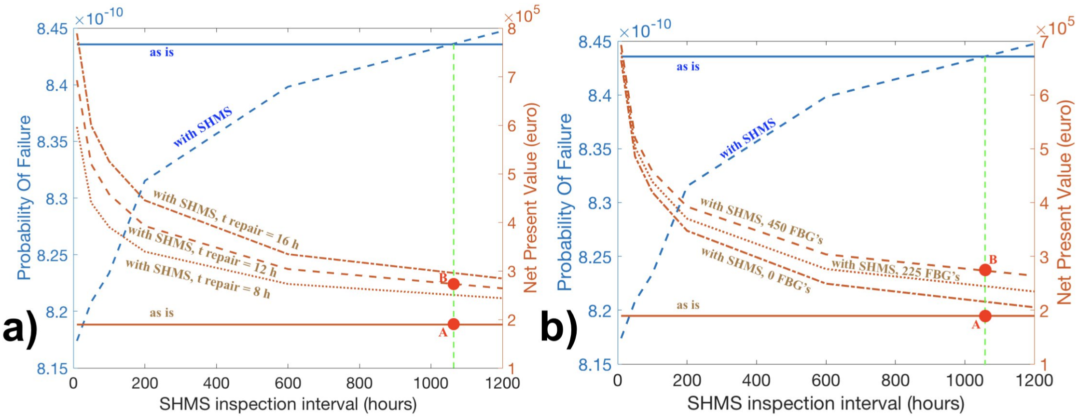

Figure 3: comparison of NPV between the two scenarios with sensitivity analysis about a) time to repair the blade; b) number of FBG sensors charged to the customer

The sensitivity analysis about the time to repair the blade equipped with FBG sensors, presented in Figure 3a, shows a NPV equal to 2.726×10^5 € for a repair time of 12 h, which is higher than the NPV in the scenario "as is", equal to 1.894×10^5 €. However, even considering a repair time equal to 8 h, corresponding to the time to repair the blade in the scenario "as is", the scenario "with SHMS" seems not to provide any economic benefit. Another sensitivity analysis is performed about the number of sensors charged to the customer. In fact, regardless of the number of sensors embedded in the blade, the Original Equipment Manufacturer (OEM) can decide whether to charge or not the extra cost of the sensors to the customer. 3 cases are considered, in which the OEM charges the cost of 450, 225, and 0 sensors to the customer. It can be observed that such parameter plays a significant role in the NPV, passing from a NPV of 2.726×10^5 € if all the 450 sensors are charged to the customer to an NPV of 2.149×10^5 € if no sensor is charged to the customer. However, even if the cost of the spare part is equal to the one in the scenario "as is", no economic benefit is achieved using the SHMS.

4. Conclusions

The study proposed some applications of a FBG-based SHMS in different lifecycle stages of a composite helicopter tail rotor blade. It was found that the SHMS could provide economic benefits in the BOL stage if a sufficient saving in the number of curing cycle is achieved during the development of the curing cycle. It was also found that an economic benefit could be obtained if a sufficient reduction in the number of blades tested is achieved thanks to the higher accuracy in the strain sensing of FBG sensors compared to strain gauges. Considering the MOL phase, the economic impact of the SHMS was found to be negative on the lifecycle of the blade. This is due to the high number of impacts at which the blade is subjected during the operational life, which lead to frequently repair or substitute the blade with higher costs compared to the scenario "as is". In fact, a sensorized blade shows a higher complexity in the repair operations and higher costs with respect to a standard blade. Future works will be needed to investigate the economic impact of SHMS applied to structural elements internal to the structure of the rotorcraft: in this way the benefits of the SHMS would be much more exploited, avoiding the disassembly of the surrounding structural elements if not needed.

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