Prevention of Human Errors in the Visual Inspection during Overhaul of Aeroengines – A Case Study

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Abstract. The statistics of accidents in air transport show that human errors are responsible for most of these accidents. As technology advances over the years, its complexity increases. These advances bring new frontiers of performance, efficiency, and sustainability. New risks are introduced in the production and use of these technologies, so visual inspection becomes a layer of protection against system failure. In aero-engine overhaul activities, identifying the points of inspection and the factors that impact the results is fundamental. An engine failure during a flight may cause a forced landing and, tragically, kill several people. This reality makes it essential to identify the inspection points, the impacting factors, and the most significant actions associated with each factor and prioritize them during aero-engine processes.
The high number of inspection points brings complexity, which usually happens in most repair stations. This fact was observed within a large repair station located in South America. The visual inspection in the engine overhaul is intended to detect nonconformance to the OEM Manuals. Based on the Maintenance Manuals, inspectors inspect hardware and make the best decision about the conformance. Inspectors are human beings who make mistakes, thus contributing to a system failure. This study aims to detail the inspection points in an engine overhaul process and show which factors impact the result of the visual inspection. It also presents the most significant actions associated with each factor to reduce the risk of operational failures caused by human errors during a visual inspection. As a methodological approach, the authors researched the state-of-the-art literature to identify which factors impact the result of the visual inspection, and a case study was conducted in the repair station. As a result, a process map was prepared to show the inspection points. The impacting factors were defined, and the most significant actions associated with each factor were obtained by a survey conducted with inspectors from the reair station. The results obtained from implementing the actions were reduced operational errors and costs of quality, increased service reliability, increased productivity, and increased customer satisfaction. The conclusion is that the study can help optimize visual inspection. As expected, the contribution is significant.
Keywords: Human Factors, Visual Inspection, and Aeroengine Overhaul, Quality

1 Introduction

Man has always dreamed of flying, arousing the interest of scientists, scholars, inventors, and entrepreneurs from ancient times until today. The airspace is a space used as a means of transportation in civil and military aviation. Civil aviation sector activities and aeronautical infrastructure are controlled by certifying agencies that aim to maintain flight safety. The activities of the aviation system are divided into operation, airworthiness, maintenance, certification, licensing of personnel, management, and air traffic safety. Thus, aero-engine maintenance is paramount and must be carried out correctly to maintain flight safety and improve airworthiness and reliability. The maintenance of aero engines is divided into complex steps, starting with the engine's arrival at the repair station and ending with the engine test. The engine is disassembled, cleaned, repaired when necessary, assembled, and tested. Aero-engine maintenance and inspection are fundamental in maintaining their physical and material integrity. Preventing wear and deterioration of parts and equipment through preventive inspection is crucial. An early diagnosis of possible wear, deterioration, or corrosion that could lead to an air disaster is crucial to keeping the crew's life safe. Inspections are visual and manual examinations. They are crucial for determining the condition of a component or detecting flaws. An engine inspection can be anything from simple to detailed examinations. Scheduled general and periodic inspections are essential to a maintenance program. Regulatory scheduled inspections and preventive maintenance are paramount to maintaining flight safety. Operational risks and equipment failures are reduced when wear and minor defects are detected in advance and corrected as soon as possible. Inspections are of paramount importance. Different types of inspections are performed, from pre-flight inspection to inspection prior to delivery of the aircraft for service and the majority of them are visual inspections.. According to official records of accident prevention and investigation agencies, human error is responsible for 80% of airplane accidents. The causes of the error can be external or internal. According to Brum [1], many employees do not know how to separate personal from professional lives leading to conflicts or distractions, lack of cognitive abilities, and lack of decision-making power, among other factors. The organization is responsible for managing these conflicts and ensuring that its employees obtain good results with safety and quality. This study aims to contribute to the studied company and others aviation maintenance companies in proposing actions to reduce the risk of human failure during the inspection. Human failure is a current problem faced by the studied repair station. The study used a survey to help prioritize the actions to reduce the risks that affect this type of operation. Its main objective was to identify the inspection points in the overhaul process and impact factors and list and prioritize the necessary actions to reduce the risks of operational failures caused by human errors during visual inspection. Research in the scientific database was conducted with the keywords: Aeronautical Maintenance, Human Error, Visual Inspection, Human Factors, and Quality. The engine overhaul process was mapped out to define the inspection points. A survey was carried out to define which factors impacted the visual inspection of aero-engines and the respective actions associated with each factor. The human body is subject to infinite environmental variations, and a simple variable can impact man's activities, such as sleeping time, food, environment temperature, and physical and emotional body, among others. When thinking about human potential, one of the biggest problems ever studied is human error, which is incorrectly given as the cause, and not as a consequence of several accidents. It is essential to define which factors impact the result of visual inspection of aero engines and the respective actions associated with each factor. Today's technological advances have brought about highly efficient equipment, but of very high complexity, containing thousands of critical components for its safe operation. Since there are thousands of associated risks and only a few resources to treat them, a reasonable inspection is essential to avoid accidents.

Previous studies presented herein do not specifically address the practical problem repair stations face regarding visual inspections. This study completes this gap and aims to propose actions to prevent Human Errors in the Visual Inspection during the Overhaul of Aero engines. It is essential in the current technological moment due to the feasibility of execution. Future studies can be developed from this research, mainly by verifying that it is possible to prioritize critical risks in inspection through practical actions to reduce the number of accidents and bring benefits to humanity.

The research questions that drove this study are:

Research Question 1: What are the inspection points in an engine overhaul process, and what factors most impact the outcome of visual inspection of aero-engines?

Research Question 2: What are the most significant actions associated with each factor to decrease the risk of operational failures caused by human errors during a visual inspection?

This study was structured as follows: The first section presents the introductory part of the research, with the determination of objectives, problem, justifications, the importance of the study, delimitation of the research, and the questions to be addressed throughout the study. The second section presents previous studies on Human Factors in Aviation, the third on Overhaul of Aero engines, the fourth on Visual Inspection. The fifth section defines the methodology used in the study, detailing the tools used to achieve the research objectives. The sixth section presents the results with details of the case study, a description of the company under study, data collected in the company, and the theoretical framework. The seventh section presents the analysis and discussion of the results. Finally, the eighth section presents the study's conclusion and its final considerations with suggestions for future research

2 Human Factors in Aviation

When talking about Risk in Aeronautics, the concepts of Human Error, Human factors, and risks implicitly come to mind. According to ICAO (International Civil Aviation Organization), the risk is the probability of injury to someone, equipment failure, material loss, or reduced ability to perform the prescribed function, measured in probability and severity. According to the FAA (Federal Aviation Administration), risk is the composite of the predicted severity and the probability of the potential effect of a hazard in the worst credible system state. Human error is defined as the failure of planned actions or the execution of a specific task to achieve the desired goal without the intervention of some unexpected event. [2]. According to Wickens, Gordon, and Liu [3], Human Error is the inappropriate behavior of human beings that reduces system effectiveness or system safety, which may or may not have material or human losses. An error can be classified into active, latent, and omission errors. Active. According to Wurmstein, Shetler, and Moening [4], Human Factors is the science of analyzing the limitations of humans and their interaction with the environment and preventing or mitigating of the inevitable human error. According to Weber [5] Human Factors refer to the study of human capabilities and limitations offered by the workplace. It is the study of human interaction in their work and life situations. According to the FAA, The Instruction Manual on Human Factors from ICAO [5] points out that "Human Factor is an expression that has yet to be clearly defined, given that when such words are used in everyday language, they usually refer to any factor related to human beings. The human element is the most adaptable and valuable part of the aviation system but is also the most vulnerable to influences that may adversely affect its behavior. Perboli et al. [6] emphasize the importance of welfare, safety, and the individual's efficiency. In aviation, the human factor study encompasses all aspects of human behavior and performance: decision-making and other cognitive processes. According to ICAO [5], the human factors task aims to enhance aviation safety by making States more aware and responsive to the importance of the human factor in civil aviation operations by adopting human factors texts and practical measures. As per CAA CAP 719 [7], lack of communication between technicians and stakeholders (interested parties) is a critical human factor that can result in inadequate, incorrect, or faulty maintenance. Zimmermann and Mendonca [8] retrieved detailed accident information, including causal factors, from the National Transportation Safety Board (NTSB). The findings indicated that maintenance activities, specifically regarding the adequacy and proper use of maintenance instructions, are impacted mainly by human factor elements, such as the overall organizational environment and the available resources. Landry [9] discussed the human factors principles regarding these types of automation in the air transportation system. Karunakaran et al. [10] studied the needs of human factors in Indian aircraft maintenance programs and their effect on profitability.

3 Overhaul of Aero engines

The maintenance or overhaul of aero engines is performed at specified intervals. The OEM usually establishes these intervals through flight hours or cycles in which the engines have been operated. The maintenance schedule of these engines must be rigorously followed because studies show that exceeding this time can damage the engine's components. In aircraft maintenance, rules must be followed, and the technical competence of the maintenance employees must be monitored. According to Wang et al. [11], allocating specialized labor in aeronautical maintenance is difficult. Wakiru [12] provided insights into articulating imperative effective maintenance strategies, benchmarking, and challenges in their implementation, considering the different operational contexts. Preventive maintenance is the practice of replacing components or sub-systems before they fail, usually with a particular frequency or under inspection and testing. It is intended to maintain the continuous operation of the system. Moayed & shell [13] stated that corrective maintenance occurs after identifying and diagnosing a problem. During these diagnoses, the maintenance technicians should identify the components that presented failures and take their repair actions. Predictive maintenance is associated with the continuous monitoring of the operating limits of a system or component, and it is associated with a possible functional failure of a component. Sharma and Rai [14] conducted a comparative study between the classic preventive maintenance policy and a developed one, and the improvement in availability, mean time between failures, and reduction in maintenance cost was registered.

4 Visual Inspection

Visual inspection is visual and manual examinations to determine the condition of a component or engine. Depending on the repair station, an engine inspection may require a detailed examination comprising a complete disassembly and the use of complex inspection aids. Drury [15] stated that inspection tasks are characterized as a careful search for non-conformity of products, in which two main functions are executed: "visual search" and "decision making." Okimoto's [16] point of view shows that a successful inspection happens when these two functions have reached the maximum performance index. Okimoto [16] points out as determinant elements for the construction of the structure of analysis and diagnosis of visual tasks the following: inspection time, visibility factors (size, shape, position, location, color, brightness, contrast, and variations in signal contours), decision process (decision about information that has been perceived), inspection yield (comparison between experienced and novice inspectors), inspected areas (places of greater or lesser privilege during inspection, personal preferences, uniformity or heterogeneity of the quantity and rate of appearance of signals), the complexity of the task (changes in the behavior of the visual scanning), formal subjectivity (individual interest in the task) and scope of the causes of inspection errors (non-detection of certain defects - discovery errors - and false diagnosis - errors of identification/discrimination, interpretation, decision).
Mandatory inspections are designed into the maintenance programs that customers have approved with the regulatory agencies (local government authorities or civil aviation agencies). Targeted inspections occur when the engine suffers some kind of problem during its useful life, such as DODs, FODs by Bird Strikes, FODs by runway debris, unusual component failures, and others. The following variables may affect failure detection: brightness, the extent of the area to be inspected, the contrast of the source of stimulus with the adjacent area, the existence of adequate inspection tools (scribbler, micrometer, magnifying glasses, etc.), excessive noise, excessive pressure, lack of communication, lack of training, lack of organization, lack of standards for visual comparison, ergonomic factors.

Aust et al [17] studied the inspection of engine blades and applied a systematic search strategy focusing on the edges, showing a better defect discrimination ability. This observation was consistent across all stimuli, thus independent of the influence factors. The conclusion was that eye-tracking identified the challenges of the inspection process and errors made. A revised inspection framework was proposed based on insights gained and supports the idea of an underlying mental model.Kujawińska and Diering [18] discussed the impact of the organization of the visual inspection process on its effectiveness and on the efficiency of the manufacturing process. The study showed a significant difference between two ways of organizing visual inspection in the technological line. The conclusion of the study was to organize organoleptic (also known as sensory) inspection in the line in such a way as to allow the extraction of non-conforming products from the stream, and not the opposite.

5 Methodology

A case study was carried out in the operational area of an aeronautical engine company. This chapter presents the methodological structure used to prepare the study. The steps used in the research to attain the result are shown in Fig. 1. In the first step, the authors analyzed the theoretical framework and scientific literature to obtain publications on the subject under study using the keywords: Human Factors, Visual Inspection, and Aeroengine Overhaul, Quality. The second step mapped out the engine overhaul process to show the inspection points with help from inspectors e engineering areas. In the third step, a list of actions to improve the inspection process was prepared, and the factors impacting the inspection were defined. A survey to be responded to by inspectors was prepared to gauge the actions' association with the impacting factors. In the fourth step, the data generated from the survey were analyzed to find the most impactful actions and factors. In the fifth step, the company identified the actions and impacting factors. In the sixth step, tools and practices are recommended for improvement. In the Seventh Step, the tools and practices are implemented, and in the last step, the results are analyzed.

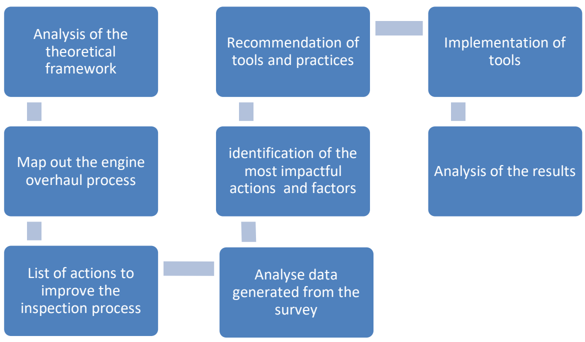

Fig. 1. A Methodology steps

6 Results

The authors prepared a process map with support from all stakeholders involved. Fig 2 shows the process flow within an aero-engine repair station and the inspection points, from receipt of the engine to its delivery. These processes are divided into steps. The illustrated inspection process includes several types of sequential inspection processes performed in the company - this sequentiality may not occur in some scenarios because some parts may be rejected in the middle of the process. However, after the complete or partial overhaul, it is inevitable that in case of rejection in the engine test, it may return to previous steps depending on the reason for the rejection.

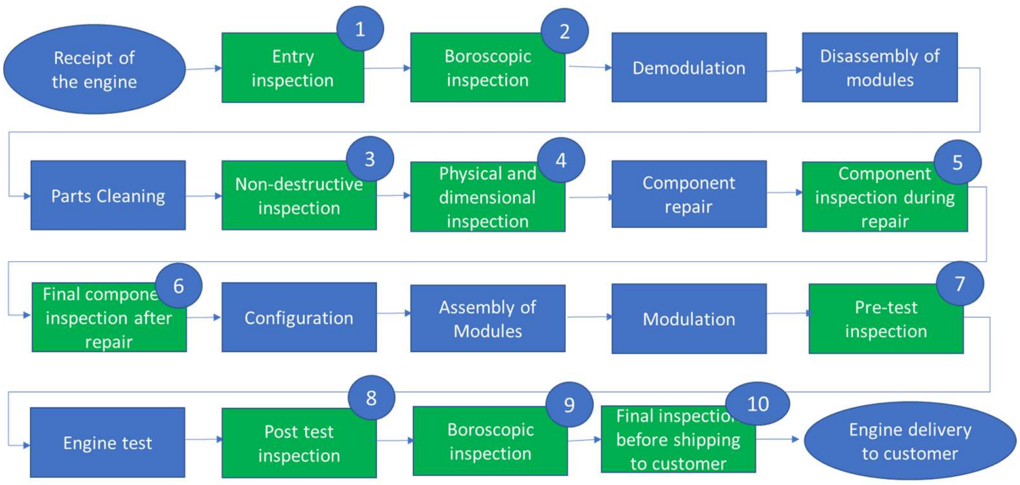

Fig. 2. Process flow within an aero-engine repair station.

The process begins with the receipt of the engine in the company, which arrives by truck. The incoming inspection is then performed, which will report the conditions and needs of this engine, which will be evaluated against the customer's scope. After this analysis, the type of service will be determined. The engine can be completely overhauled or repaired, i.e., the repair will be performed only to change some component or specific area. At inspection point 1, an inspector performs a preliminary inspection to determine, through visual inspection together with the customer's scope, any abnormality of this engine, such as failures and broken components, to determine the type of service work to be performed. At point 2, a borescope inspection is performed to look for damage or defect of a component such as piping, components, or engine internally without disassembly. At the point of Inspection 3, a non-destructive testing inspection is performed. It does not damage or alter the component and aims to find some kind of damage or defect through ultrasound, radiography, or liquid penetrant. At Inspection Point 4, a detailed visual and dimensional inspection is performed. At Inspection Point 5, an inspection of the component during repair is performed to determine the condition of the parts and observe if it has not suffered any damage during transportation or the required repair. In Inspection Step 6, the final component inspection after the repair is performed to verify that the required repairs have been performed correctly following the maintenance manual. In inspection Step 7, a pre-test inspection is performed after finalizing the engine assembly in order to ensure the service was correctly performed. At point 8, an inspection is performed after the engine test to check if the engine passed the test or if there was any component failure, such as oil leakage or abnormality. At inspection point 9, a borescope inspection is performed to ensure that the entire process was executed correctly with quality and safety in the internal part. At inspection point 10, a final inspection is performed before sending to the client to ensure that the service was performed with total quality of the product and sent to the client, ensuring the quality of service and flight safety. A survey was conducted with inspectors to define which factors impact the result of the visual inspection of aero-engines and the respective actions associated with each factor. The first part of the survey shows the questions directed to identify the participants' professional experience. The questions were as follows: What is your length of professional experience? Do you work/work directly with visual inspection or another type of non-destructive testing (NDT/NDT)? Fig 3 shows that 39.3% of respondents work or have worked in the profession of visual inspection or other non-destructive testing (NDT) for more than 15 years, 25% of respondents have worked or work in the function between 11 to 15 years, 25% work or have worked in the inspection from 6 to 10 years, 10.7% of respondents work in the function less than 5 years. Fig 4 shows that 82.1% of respondents had experience with a visual inspection.

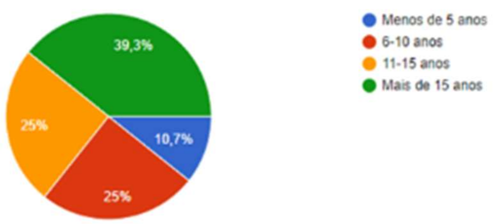

Fig. 3. Time of experience

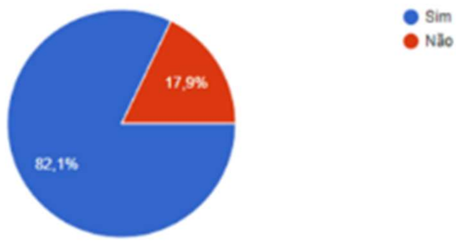

Fig. 4. Experience with visual inspection

The second part of the survey shows which good practices (rows) can influence the CSF - Critical Success Factors (columns) in a visual inspection process. The questions and the impacting factors are shown in Table1. It shows the distribution of the number of answers from the survey related to each question, that is, the factor that most influences visual inspection according to each question.

Table 1. Results from the survey

		Inspection Performance	Environmental Factors	Organizational Factors	Individual Factors	Social Factors	Training	**Total**
Action	Description (Action)	1	2	3	4	5	6	N/A
1	Keep project documentation up-to-date and available	22	3	18	9	4	13	**69**
2	Validated procedural guidelines	16	2	15	5	3	20	**61**
3	List of available tools and supplies	15	0	19	8	1	15	**58**
4	Mental model of the inspection	14	2	8	17	7	19	**67**
5	Knowledge of possible defect types and probabilities	19	6	9	11	2	24	**71**
6	Use correct terminology	18	1	10	10	4	21	**64**
7	Compatible inspector experience	16	2	9	15	2	21	**65**
8	Calibrated and maintained equipment	21	2	20	7	1	13	**64**
9	Adequate place for inspection	19	3	20	6	3	10	**61**
10	Access equipment available (scaffolding, ladders, etc.)	12	10	21	2	2	13	**60**
11	Correct support equipment (magnifying glass, mirror, etc.)	17	4	19	8	2	12	**62**
12	Time and motion planning	15	4	20	13	4	10	**66**
13	Properly designed access (entry/exit)	11	8	20	3	2	9	**53**
14	Proper stowage of inspection equipment	17	6	19	10	2	10	**64**
15	Ergonomically designed equipment	15	6	18	11	7	8	**65**
16	Sufficient inspection time, including intervals	20	1	17	11	3	10	**62**
17	Definition of the inspection level (general, detailed, area, part)	21	5	13	13	4	18	**74**
18	Observe correct lighting (ambient and portable ratio)	19	17	16	12	2	13	**79**
19	Avoid improvisation	16	2	14	15	4	19	**70**
20	Correct definition of FOV (Field of View)	17	4	6	6	1	14	**48**
21	Maintain a history of known defects	16	1	14	12	1	17	**61**
22	Correctly cleaned inspection target	21	4	9	13	3	17	**67**
23	Use visual indications and markings, according to standards	22	1	11	14	1	21	**70**
24	Use senses other than sight when possible	19	4	7	16	2	17	**65**
25	Correct classification of defect severity	22	2	7	14	2	19	**66**
26	Consider parallax phenomenon (use of adjustment formulas)	20	4	5	15	1	21	**66**
27	Define defect x sampling parameters	22	0	11	11	1	17	**62**
28	Encourage the exchange of experiences between inspectors	16	3	15	15	13	15	**77**
29	Action/decision policy in case of defect	16	1	16	6	3	17	**59**
30	Appropriate recording system, allowing the best description of the inspection	17	1	21	5	2	17	**63**
31	Constant automation of the process, maintaining flexibility	14	3	20	5	3	13	**58**
32	Check if the inspected item returned to its original functional condition after inspect	22	1	7	11	3	15	**59**
33	Ensure the correct levels of access to information	12	2	19	8	5	17	**63**
	TOTAL	**580**	**117**	**476**	**341**	**105**	**521**	

Table 1 shows a summary of the results from the survey. The lines and columns marked in the dark blue present the highest score and are considered the most important. The inspection performance is the factor that is related to the highest probability of errors, followed by training since the lack of adequate qualification of labor interferes directly in the execution of the inspection. Organizational factors come in third and are also a crucial factor in the success of the inspection since an organized and clean environment is paramount for quick and safe work. Examples of actions to improve organizational factors are Poka-yoke, Lean initiatives, and Kanban implemented in inspection areas. The most critical actions are 1 - knowledge of possible defect types and probabilities, 2 - the definition of the inspection level (general, detailed, area, part), 3 - correct lighting (ambient and portable ratio), 4 - avoiding improvisation, 5 - using visual indications and markings according to standards and 6 - encourage the exchange of experiences between inspectors.

7 Discussion of Results

The results show that the visual inspection process begins with incoming inspection after the receipt of the engine in the company. This first inspection report the conditions and needs of the engine, which is evaluated against the customer's scope. After this analysis, the type of service is determined. The engine can be completely overhauled or repaired, i.e., the repair is performed only to change some component or specific area. Afterward, the engine is disassembled, and different kinds of visual inspections are performed in different stages of the overhaul process. The literature review revealed several feasible actions to improve the visual inspection in all stages. The data obtained with the survey allowed the association of the several actions to the six CSF - Critical Success Factors (columns). It can be seen that the team of inspectors understands the importance of the proposed actions and that it was still necessary to improve the visual inspection process by addressing the most critical CSF with a focus on the most critical actions. It was necessary to engage employees by better participation in improving the inspection workstations and the process. Thus, the team's engagement in the workstation organization with 5S, Kanban, and Poka occurred rapidly since they understood the main consequence of an effective visual inspection process, which is the improvement of quality and safety.

As a result of this study, the improvement in the knowledge of possible defect types and probabilities occurred with comprehensive hands-on training and a visual inspection certification process for all the inspectors. The engineering area addressed the definition of the inspection level (general, detailed, area, part) by more detailed and complete inspection instructions. The correct lighting (ambient and portable ratio) was ensured by monitoring the light intensity in each inspection workstation. The avoidance of improvisation was addressed in the training section with the inspectors. The use of visual indications and markings according to standards and exchanging experiences between inspectors were also encouraged during training sections. Some methods such as Lean, poka-yoke, Kanban, and Kaizen were introduced to improve the visual inspection process and organizational factors. As a result of all these interventions, it was observed a significant reduction in operational errors; a reduction in non-quality cost, an increase in product or service reliability; an increase in productivity due to employee-related benefits and customer satisfaction.

8 Conclusion

Critical human factors negatively impacting the visual inspection results can be avoided through preventive actions and organization in the work environment, whose purpose is to reduce operational errors and avoid airplane accidents performed by human errors. In response to the first research question: *What are the inspection points in an engine overhaul process, and which factors impact the result of visual inspection of aero-engines?* A process map is presented to show the inspection points, and the most impacting factors were inspection performance, training, and organizational factors. In response to the second research question: *What are the most significant actions associated with each factor to decrease the risk of operational failures caused by human errors during the visual inspection?* The most significant actions associated with each factor were: 1 - knowledge of possible defect types and probabilities, 2 - the definition of the inspection level (general, detailed, area, part), 3 - correct lighting (ambient and portable ratio), 4 - avoiding improvisation, 5 - using visual indication, 6 - markings according to standards and 7 - encourage the exchange of experiences between inspectors. Some methods, such as Lean, poka-yoke, Kanban, and Kaizen, were introduced to improve the visual inspection process.

The company's benefits were reduced operational errors, reduced non-quality costs; increased product or service reliability increased productivity due to employee-related benefits; and customer satisfaction. From this work, several multidisciplinary studies could be carried out, such as 1 - The use of methods that facilitate the inspection process to maintain quality and safety; 2 - Training improvement so that employees are constantly trained and updated in critical inspections as in aeronautical maintenance, being possible to analyze a larger population. 3 – The use of adequate tools for each type of process and adaptation to the innovation of the technology, which promises the process's agility, maintaining efficiency in the dimensional precision as the 4D.

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