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CINNABAR PROJECT – COST-BENEFIT ANALYSIS OF DIGITAL PROCESSES FOR NON-DESTRUCTIVE INSPECTIONS OF AIRCRAFT STRUCTURES

Johanna Aigner[1], Ann-Kathrin Koschlik[1], Hendrik Meyer[1], Florian Raddatz[1] & Gerko Wende[1]

[1]German Aerospace Center (DLR) - Institute of Maintenance, Repair and Overhaul, Hamburg, Germany

Abstract

The outlined study focuses on the cost-benefit analysis of implementing digital processes for structural aircraft inspection using state-of-the-art laser-scanning technology, augmented reality (AR), and digital twins. Traditional aircraft inspection methods need to meet high quality standards in terms of accuracy, reproducibility and documentability and are therefore known to be time-consuming and labour-intensive, leading to high costs and potential safety risks related to human factors. By substituting manual maintenance tasks through digitally supported approaches and implementing a digital thread, the inspection processes can be streamlined and made more efficient. This publication aims to analyse the initial investment effort required for implementing these digital processes and compare it to the potential cost savings and benefits in terms of working time and quality. Different process modifications to the current dent-and-buckle inspection process are proposed and closely analysed. The findings of this analysis will offer valuable insights for aircraft maintenance companies and decision-makers regarding the feasibility and potential benefits of adopting digital processes for structural aircraft inspection.

Keywords: Aircraft Maintenance; Dent & Buckle; Mixed Reality; Scanning; Non-Destructive Evaluation

1. Introduction

1.1 Background

Digitalization and automation are increasingly used in various industries and sectors. In aviation maintenance, repair and overhaul (MRO), the arrival of these new technologies has opened a new era: Leaving the world of scheduled maintenance behind, pro-active maintenance strategies such as predictive or prescriptive maintenance stream line maintenance activities based on current and predicted conditions [1] and highly connected digital twins [2]. While the strategic benefits are intensively discussed and favored [3, 4], the implementation of these technologies and operational realization of such a change still faces some major challenges. Special attention is given here to processes in MRO. Current manually-executed, in paper-format documented processes often lack an alignment of process steps and require a large amount of human interaction. A shift towards data-driven processes benefits from an increased efficiency and thus more profit. Hence, inspection methods need to change from purely visual inspections to automated inspection tools enabling data generation, storage, processing and provision [5]. For the use-case of a dent-and-buckle check, an automated inspection process is developed in the project CINNABAR [6, 7, 8] as shown in Figure 1.

The introduced inspection process still requires human interaction, so there is the potential of further digitalization and automation. In order to assess how digitally-advanced the developed approach performs, its digitalization degree is measured by a digital maturity model. Such a model is used in both industry and science to classify the degree of digitalization of an institution. As there is no standardized metric to assess the degree of digitalization of inspection procedures, some maturity models found in the literature are compared in this paper and adapted to the use-case to assess the digitalization degree of the proposed process. Processes with a higher digital maturity do not

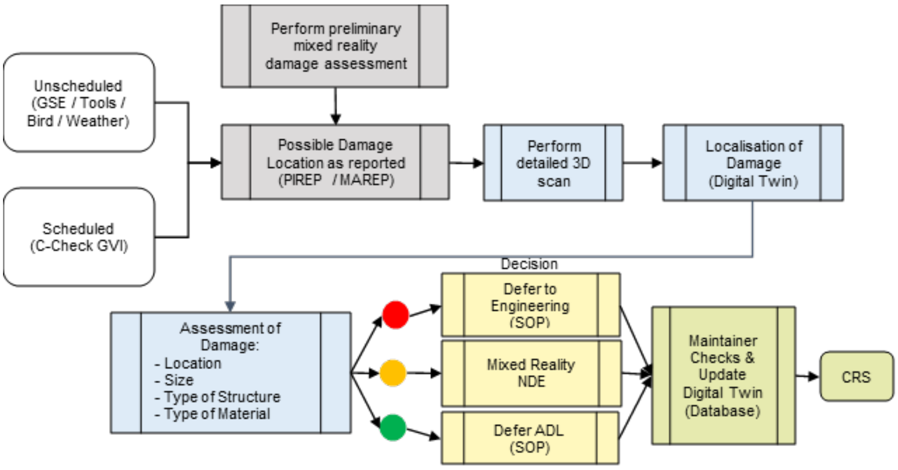


Figure 1 – Inspection process in the CINNABAR project as developed in [6].

necessarily perform “better”, e.g. if the implementation expense exceeds the outcome. In order to assess processes, a variety of process assessment models exist. In this publication, the gained benefits of the CINNABAR inspection process are compared to the implementation expense by a cost-benefit analysis. However, the benefits may be measured in multiple ways, e.g. economically (time and cost savings), ecologically (emissions and energy savings), socially (human factors, social aspects) or in terms of an improved quality (accuracy, reproducibility). The implementation cost is usually in terms of economical expenses, but also human factors like the capacity of familiarization to new technologies may be taken into account. As efforts and potential revenues might arise at different stakeholders, e.g. MRO and airline, the overall system efficiency needs to be considered in order to assess a modification. An increased efficiency of the overall system, however, is no proposal for the introduction into industrial processes, if e.g. an implementation expense at one stakeholder goes along with a revenue increase at another stakeholder in the MRO landscape. The cost-benefit analysis for processes of different digitalization degrees within one organization allows for deciding about the implementation of modified, digitalized processes. Therefore, from an MRO's perspective, it is addressed in this research paper. This paper is structured as follows: In a literature review, both process assessment models as well as digitalization maturity models for processes are described in order to assess the degree of digitalization of the modified inspection process and compare the performance of the CINNABAR inspection process with a conventional one. These use cases are described and assessed with respect to the identified models that are adapted to inspection processes in aviation MRO. Based on the digitalization assessment and cost-benefit analysis of these use-cases an estimation of the desired degree of digitalization and automation for the dent-and-buckle inspection process is provided in the end.

1.2 Research Objectives

The potentials of digitalization in aviation MRO processes are shown in various publications [9, 10]. However, the introduction of digitalization and realization of automation requires effort to overcome the faced challenges. The investment expense shall be balanced against the added values in a cost-benefit analysis in order to validate a process modification. This analysis should be regarded against the background of the achievement of a digitally more mature inspection process. Therefore, the research question in this publication is as follows:

What are the measurable benefits of a digitalized inspection process for dents in aircraft structures against the implementation cost?

In order to assess this question, the following three questions are investigated in this publication:

- How can processes be assessed in terms of cost and benefits qualitatively and quantitatively?
- How can the digitalization degree of processes be described and measured?

- How do current and digitally supported inspection processes perform with respect to these metrics?

2. Method

2.1 Methodology

In order to answer the three questions, first a literature review is conducted for process assessment models with focus on cost-benefit analyses. Then, digitalization maturity models are researched in literature. The current as well as the digitally supported inspection process developed in the CINNABAR project as use-cases are described and then assessed with regard to both their digital maturity and cost-benefit performance. After this assessment, the results are discussed in order to show the potentials of the modified process without neglecting its implementation effort.

2.2 Literature review: Process assessment models

Processes can be assessed in different ways, for example either in terms of efficiency or effectiveness, qualitatively or quantitatively and ex-ante or ex-post: Whereas effectiveness evaluates the "Extent to which planned activities are realized and planned results are achieved" [11], efficiency assesses the "Relationship between the result achieved and the resources used" [11]. Another distinction is between quantitative, i.e. value-based, measurable assessment and qualitative assessment which is rather descriptive and used for the evaluation of indicators that are harder to measure in a numeric way, like human factors. Ex-post assessments evaluate how a modified process performs, often compared to the original, unmodified process. This assessment gives valid values for the process modification, however, the modification needs to be implemented before it can be assessed. In contrast, ex-ante process assessments aim to predict process modifications before they are realized. Therefore, ex-ante assessments can be used to decide whether or not a process modification is valuable [12, 13]. However, as this assessment is based on assumptions, models and possibly simulations, the actual modified process could perform differently. These assessments can be performed in regard to various aspects like economy, ecology, human factors or technology.

As in aviation MRO, the activities and results are regulated by authorities like the European Union Aviation Safety Agency (EASA) or Federal Aviation Administration (FAA), the effectiveness cannot be improved without changes in regulations. However, the efficiency has the potential to increase. When introducing new technologies into companies, the decision-makers have to decide if the investment cost outweigh the realizable benefits in terms of efficiency increase [14]. An established method for this decision is a cost-benefit analysis. Whereas measures like duration and cost can be captured quantitatively, it may be difficult to assess qualitative benefits [15, 16, 17]. These non-monetary benefits and their potential agglomeration effects, however, may outweigh the economic expenses such that they should be included in the analysis as well [18, 19, 20]. Various researchers investigate in monetizing qualitative factors [16, 19, 21]. Therefore, in a literature review, cost-benefit-analyses in different industries are scanned. The regarded dimensions are summarized in Table 1.

The scanned literature includes analyses in different industries like health care [15], transportation [16, 20] and chemistry [24, 26]. As can be seen in Table 1, besides the economic dimension which is included in each analysis, many qualitative dimensions as quality and social aspects are included as well. As many authors do not differentiate between ecological and environmental aspects, they are treated as equivalent in Table 1. In [23], the cost for realizing a modification is denoted as investment instead of expenses as the cost is low compared to the additional contribution.

Additional to different dimensions as shown in Table 1, cost-benefit-analyses are distinguished in the three categories eonomic, analytic and strategic apporaches [37] which should be combined for investment justification. Recent publications on cost-benefit-analyses related to the use-cases in the CINNABAR-context evaluate suitability and utilization of virtual reality applications [12] and a decision-support system based on a 3D-scanning tool [38]. In [12], operational and strategic costs and benefits for VR applications as well as influencing factors for the profitability of investment are provided. The analysis in this publication is based on the considerations in [12].

Table 1 – Dimensions in cost-benefit-analyses in scanned publications.

Source	Economical	Duration	Ecological	Social	Technological	Quality	Resources
[22]	X		X				
[23]	X	X		X		X	
[16]	X		X	X		X	
[24]	X		X				
[17]	X		X				
[25]	X	X					X
[19]	X		X	X		X	
[26]	X		X				
[27]	X	X				X	
[28]	X					X	
[20]	X	X				X	
[29]	X		(X)				
[12]	X				X		
[30]	X					X	
[31]	X						
[32]	X		X		X	X	
[33]	X					X	
[34]	X					X	
[35]	X						
[36]	X						

2.3 Literature review: Digitalization maturity models

With the ongoing digitalization in various industries, the demand for measuring the degree of digitalization within organizations is increasing. In scientific literature, the degree of digitalization is described by the term digital maturity and its assessment is conducted by digital maturity models, i.e. [39]. Maturity can be defined as a “measure to evaluate the capabilities of an organization in regard to a certain discipline” [40]. In order to assess the capabilities in regard to digitalization, the digital maturity is defined as the alignment of an "organization’s people, culture, structure and tasks to compete effectively [...] both inside and outside the organization" [41, 42]. For quantification, digital maturity models usually use various dimensions including different subcategories representing various aspects affected by digitalization. In literature, the number of dimensions as well as their subcategories varies between the different models: In [43], existing models with a different number of dimensions are evaluated based on academic criteria. According to the authors, typical dimensions are summarized as "customer experience, operational processes, business models and digital capabilities". Another review of digital maturity models is conducted in [44] where various models with different number of dimensions are compared. Based on their scanned literature, they deduce key digital metrics for the digital transformation for organizations. Related to digital maturity models are industry 4.0 maturity models which are evaluated in a systematic literature review in [45]. Shoshin et al. [46] transferred the Industry 4.0 Maturity Index by acatech [47] to the aviation industry, see Table 2. The introduction of a preceeding first stage in a digital maturity model underlines the manual and analogue aviation sector lagging behind other industries. These models refer to the digitalization of companies and institutions. According to [48], besides the digitalization of business models, also the digitalization of processes is part of the digital transformation. Whereas the digitalization of business models aims to adapt and develop new products and services, processes are digitalized in order to increase efficiency, margins and productivity, reduce costs and improve performance [48]. An industry 4.0 maturity model based on the SPICE (Software Process Improvement and Capability dEtermination) standard [49, 50, 51, 52] is deduced in [53]. Processes in organizations are viewed holistically, including assets, data, application and organization. This holistic approach of connecting technologies and processes in an organization with their environment is continued in the digital maturity model developed in [42]. In the dimension "organization" there are five sub-dimensions called "axes": Strategy, governance, culture, human resources and processes. The maturity of processes is measured regarding the digitalization of information flows, operational performance, data management and data governance policies as well as the optimization and automation of processes, logistics, operational quality and asset management. Their deduced maturity scale, starting at the digitization stage, is extended with a first stage of hardware compliance in accordance with [46] in order to assess the digital maturity of the processes in this publication, as shown in Table 2.

Table 2 – Maturity scale for digital maturity model deduced in [42], adapted according to [46].

Level	Description
Hardware compliance	Assessment stage of hardware/software and their readiness for digital transformation Elimination of outdated hardware, software and processes Development of hybrid ecosystem is possible only
Digitization	Manual processes No knowledge of scope and impact of digital technologies Information technologies may be present, but isolated from each other
Communication	Connected IT systems Defined processes, mostly still manual Knowledge of digitalization, but no defined strategy
Visibility	Digital model of the organization Data-driven decision-making
Transparency	Establishment of digital vision and strategy Knowledge-based decision-making
Predictability	Simulation of different future scenarios, prediction of most likely ones Automated decision-making based on scenario forecasting and real-time data gathering Digital culture and strategy spread among workforce
Flexibility/Adaptibility	Complete integration of operations and processes Fully autonomous decision-making and self-adjusting capabilites Continuous education and leadership and career development

3. Description of Use-Cases

3.1 Use-Case 1: Conventional inspection process for dents in aircraft structures

As a reference, a current inspection process as shown in Figure 2 is used. The information about the process flows are based on repair manuals, the authors' knowledge about maintenance processes and expert interviews in an MRO organization (see also [7, 8]).

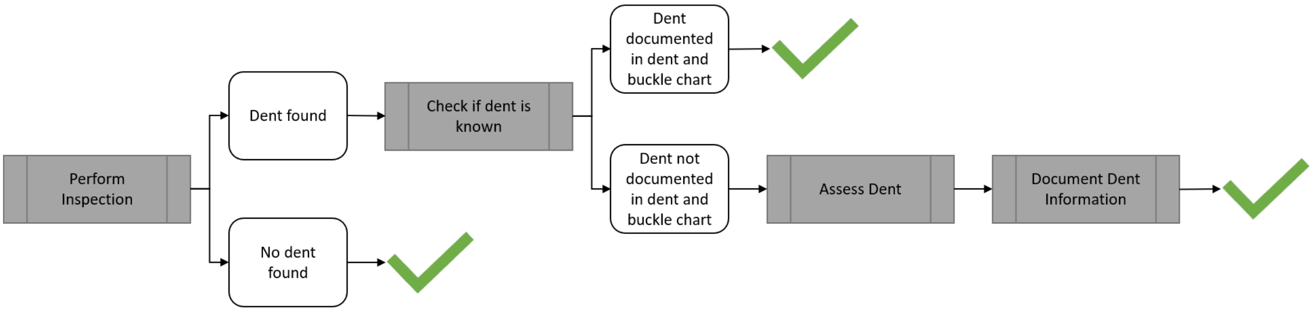


Figure 2 – Process flow of current inspection process.

A general visual inspection is performed by either the mechanic, or in a pre-flight check the pilot. If a dent is found, it is checked in the dent-and-buckle chart if the dent has already been assessed. If the dent is documented in the chart and evaluated as "fixed" or "in limit", no further actions are necessary. However, if the dent is not in the chart or in a "deferred" state, it has to be assessed in order to ensure the airworthiness. The assessment process according to [54] is shown in Figure 3.

If within a specified area further damages or repairs are found, the dent needs to be repaired according to repair instructions given by the Structural Repair Manual (SRM) or engineering. Otherwise, the dent dimensions width, depth and their ratio are measured with a dent gauge. If the dent is within the allowable damage limit, the dent measurement is documented, otherwise the dent is repaired according to repair instructions defined in the SRM or an repair design engineering organization.

For a repair definition, the engineering organization often needs more details about the actual damage geometry. Therefore, a grid as shown in Figure 4 is drawn on the dented area as well as on a photograph of the dent. Then, a mechanic measures the depth for each field in the grid and documents the value on the photograph's grid. This document can then be used by the design engineers to define a suited repair method.

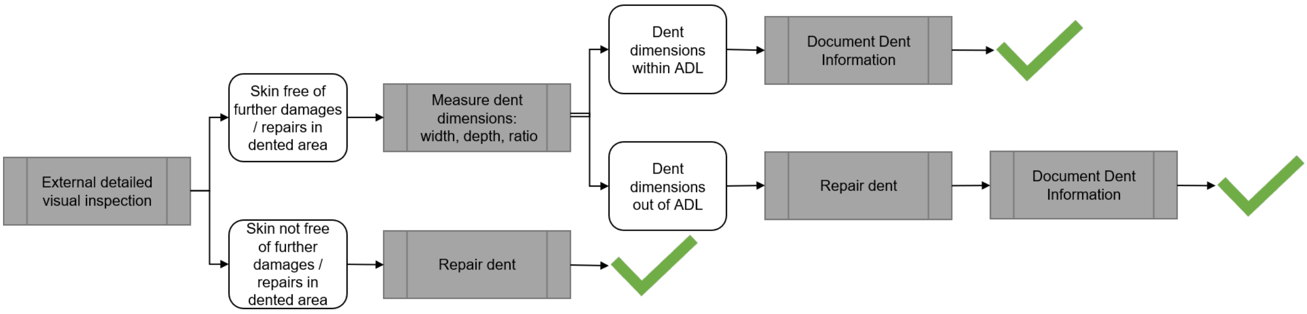
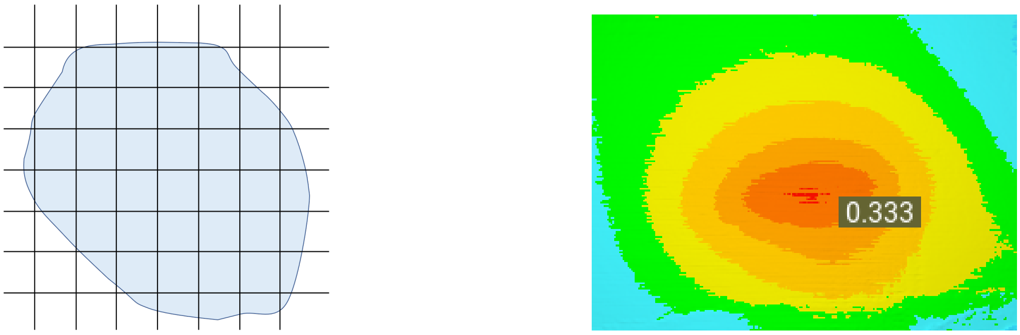


Figure 3 – Detailed description of step "Assess Dent" in Figure 2.



(a) Conventional process: Grid and manual measurement.

(b) CINNABAR process: Automated 3D scan measurement.

Figure 4 – Dent documentation for repair definition.

3.2 Use-Case 2: CINNABAR Workflow

In the CINNABAR (LoCalize vIsualize document DeNt And Buckle chARts) project, a new framework for non-destructive evaluation of aircraft structures is developed [6]. In contrast to the current inspection processes used in industry shown in the previous section, their inspection process is described in Figure 1.

An augmented reality (AR) application [7] allows for a immediate check if the dent is known (see Figure 2) as all dents documented in the dent-and-buckle chart are stored in the AR application. Furthermore, the damage assessment in terms of dimension measurement can be performed in the technology as for a found damage, the contour can be drawn by a virtual index finger [7]. This drawn shape starts the automatic calculation of damage dimensions (length, width). Further details about the application and the corresponding workflow can be found in [7]. If for the damage assessment a more detailed evaluation is needed (see Figure 4), a detailed 3D scan is performed. In some post-processing tasks, this scan can be used to localize the damage and assess it in terms of size, geometry and material characteristics. The framework for this assessment including specifications about the used scanners is given in [6]. This 3D scan can replace the detailed measurement as shown in Figure 4. It is noteworthy that both the AR application as well as the detailed 3D scan do not depend on each other and can be performed individually. Hence, for the following assessment of use-cases, instead of comparing the two processes as described, the individual as well as the combined implementation of the two technologies is considered.

4. Assessment of Use-Cases

4.1 Digital maturity of the Use-Cases

The described use-cases are first assessed with regard to their digital maturity according to the scale in Table 2.

In the current conventional inspection process (Figure 2), all tasks are executed individually and the documentation is stored in isolated documents. When introducing new digital technologies, a hybrid ecosystem will be produced as preceeding or following process steps remain non-digitized.

This is a clear indicator for stage 1, the hardware compliance stage where hardware, software and processes are assessed with regard to their readiness for digital transformation.

The AR dent localization application [7, 8] connects the dent check with the digital dent-and-buckle chart and the inspection personnel is guided through the defined inspection process. Thus, the process enriched with the AR application is classified in the communication stage.

Similarly, the automated dent recording with the 3D scanning technology needs connected IT systems and defined processes which classifies this use-case also in the communication stage.

At the current development stage of the CINNABAR process, the two technologies are developed independently. Therefore, if the preliminary dent dimension assessment with the AR application results in a need for a detailed dent recording with the 3D scanning technology, human interaction is needed to align the detailed dent scan with the localization in the AR application in a postprocessing step. Therefore, the two technologies that are both classified in the communication stage are not integrated into each other, so that the indicator "connected IT systems" is not fulfilled. However, as digital technologies are in place, this scenario is classified in the digitization stage.

As the CINNABAR project is still advancing and the aim is to align both technologies and reduce the human post-processing in order to align the detailed dent scan with the localization of the AR application, the visionary scenario after aligning both technologies is assessed as well. In particular, it is discussed if a classification in the next digital maturity stage, the visibility, is realizable within the approaches followed in the CINNABAR project. For the visibility stage, a digital model of the organization as well as data-driven decision-making are required. At the moment, the technology development is limited to the dent recording. Therefore, decisions along the process chain still require human interaction, as the decision criteria are captured in continuously revisioned repair manuals. Thus, in order to achieve the next digital maturity stage, the decision criteria, i.e. the allowable damage limits for each location on the fuselage and the current state (previous dents and repairs) need to be implemented into the virtual model. In an expert interview, a decision engineer in an MRO shop affirmed the benefit of an integrated decision-making, however, he mentioned that the implementation update of the whole documentation used for decision-making would take too much time. Therefore, an alternative, modular documentation might be necessary before actually realizing an integrated decision-making and thus, a classification in the visibility stage.

4.2 Process assessment of the Use-Cases

Process assessments using cost-benefit analyses may include various dimensions as shown in Table 1. In this publication, the realizable benefits in terms of cost savings and potential quality improvements are compared to the implementation cost.

4.2.1 Economic assessment

From an economical point of view, the CINNABAR process will only be introduced in an organization, if the expected resulting process cost $C_{CINNABAR}$ is lower than the process cost $C_{conventional}$ of the conventional process as shown in Figure 2:

$$C_{CINNABAR} < C_{conventional}. \tag{1}$$

According to [12], cost for introducing new technologies and processes into organizations consist of

- initial technology-related cost $C_{init,CI}$,
- ongoing technology-related cost $C_{ongo,CI}$,
- personnel cost $C_{pers,CI}$ and
- organizational cost $C_{orga,CI}$.

Additionally, MRO-specific tooling, spare parts, tooling, and related areas like logistics, planning, quality management that are part of a current MRO organization will stay and are therefore summarized as C_{gene} and added to the CINNABAR process cost:

$$C_{CINNABAR} = C_{init,CI} + C_{ongo,CI} + C_{pers,CI} + C_{orga,CI} + C_{gene}. \tag{2}$$

Similarly, cost $C_{conventional}$ for the conventional process consist of various cost factors, e.g. organizational cost for administration and management of the organization $C_{orga,co}$ as well as personnel cost $C_{pers,co}$ and the aforementioned general cost C_{gene}:

$$C_{conventional} = C_{orga,co} + C_{pers,co} + C_{gene}. \tag{3}$$

In order to compare the processes, the different cost factors need to be assessed and compared. The initial technology-related cost $C_{init,CI}$ [12] consist of

- acquisition of hardware (AR tool and 3D scanning device) $C_{hardwareacq}$,
- software acquisition (operating system, specific CINNABAR application software) $C_{softwareacq}$,
- consulting C_{cons} and
- corresponding infrastructure C_{infr}.

As in a digitally more mature organization, not only the dent-and-buckle assessment will be supported by AR and 3D scanning technologies, but also other processes like inspection of hydraulics or avionics and repairs, the acquisition cost for hardware and operating system of the software only proportional to the CINNABAR process should be considered for the cost:

$$C_{hardwareacq} = n_{AR} \cdot C_{AR} \cdot \text{Prop}_{AR} + n_{3D} \cdot C_{3D} \cdot \text{Prop}_{3D}, \tag{4}$$

with C_{AR} and C_{3D} the purchase cost of the AR and respectively, 3D scanning device, n_{AR} the number of AR devices in the organization, n_{3D} the number of 3D scanning devices in the organization and Prop_{AR} the proportion of the CINNABAR use-case compared to all AR applications in the organization. If, for example, AR applications are evenly used for five different processes, the proportion is $\text{Prop}_{AR} = 0.2$. Analogously, Prop_{3D} is defined. Whereas for the operating system C_{oper} of the AR and 3D scanning, a similar proportion-based calculation is necessary, the software dedicated for the CINNABAR process $C_{\text{software CI}}$ needs to be bought for each device and cannot be distributed to other processes:

$$C_{softwareacq} = n_{AR} \cdot (C_{\text{oper, AR}} \cdot \text{Prop}_{AR} + C_{\text{software CI, AR}}) + n_{3D} \cdot (C_{\text{oper, 3D}} \cdot \text{Prop}_{3D} + C_{\text{software CI, 3D}}). \tag{5}$$

Further initial technology-related cost like consulting C_{cons} and infrastructure C_{infr} are neglected in our analysis as in digitally more mature organizations we assume the infrastructure to be established and the organization's expertise to be advanced so that consulting costs are neglectable.
As for the conventional process no initial technology-related cost arise, $C_{hardwareacq}$ (4) and $C_{softwareacq}$ (5) contribute to $C_{CINNABAR}$ on the left side of (1), but not to the conventional process $C_{conventional}$.

The ongoing technology-related costs $C_{ongo,TR}$ [12] are composed of

- hardware/software update and maintenance $C_{\text{update, hw}}$, $C_{\text{update, sw}}$
- support C_{support}
- energy C_{energy}.

Whereas hardware maintenance cost $C_{\text{update, hw}}$ are distributed over all processes using the hardware, both software maintenance and update cost $C_{\text{update, sw}}$ and support C_{support} consist of a distributable proportion $C_{\text{update, sw, dist}}$ and $C_{\text{support, dist}}$ (e.g., operating system) over all processes using the technology and a CINNABAR-specific contribution $C_{\text{update, sw, dist}}$ and $C_{\text{support, CI}}$. Energy used during the

CINNABAR process are not distributable and contribute fully to the ongoing technology-related costs with C_{energy}:

$$\begin{aligned}C_{ongo,TR} = {} & n_{AR} \cdot C_{\text{update, hw,}AR} \cdot \text{Prop}_{AR} + n_{3D} \cdot C_{\text{update, hw,}3D} \cdot \text{Prop}_{3D} + \\ & + n_{AR} \cdot (C_{\text{update, sw, dist,}AR} + C_{\text{support, dist,}AR}) \cdot \text{Prop}_{AR} + \\ & + n_{3D} \cdot (C_{\text{update, sw, dist,}3D} + C_{\text{support, dist,}3D}) \cdot \text{Prop}_{3D} + \\ & + n_{AR} \cdot (C_{\text{update, sw, CI,}AR} + C_{\text{support, CI,}AR}) + \\ & + n_{3D} \cdot (C_{\text{update, sw, CI,}3D} + C_{\text{support, CI,}3D}) + \\ & + C_{\text{energy, AR}} + C_{\text{energy, 3D}}.\end{aligned} \tag{6}$$

Similarly as with the initial technology-related cost, also the ongoing technology-related cost do not have a counterpart in the conventional dent-and-buckle process and thus only contribute to $C_{CINNABAR}$ on the left hand side in (1).

Personnel costs $C_{pers,CI}$ are composed of user training $C_{UT,CI}$, management and administration $C_{MA,CI}$ and operational activities C_{proc}. In digitally mature organizations, it is expected that personnel will be familiar with the handling of digital technologies. Therefore, it is assumed that the cost related to user training will not change when compared with current, annual re-trainings. Similarly, it is assumed that in digitally mature organizations the management and organization of personnel will stay equal to current values $C_{UT,co}$ and $C_{MA,co}$ of the conventional process:

$$\begin{aligned}C_{UT,CI} &= C_{UT,co} \\ C_{MA,CI} &= C_{UT,co}.\end{aligned} \tag{7}$$

Therefore, only the operational activities change when implementing the CINNABAR process: Assuming, the salary is constant when using new technologies, the cost related to operational activities is proportional to the working hours of the mechanics and engineers. Thus, for assessing C_{proc}, the duration of the various process steps in the CINNABAR process is assessed. In the following Table 3, the process steps as shown in Figures 2, 3, 4 are compared from the conventional execution with the CINNABAR flow:

Table 3 – Process steps along the dent-and-buckle inspection process and their substitution in the CINNABAR process flow.

Process Step	Process Step Description	Applicable for	Substituted by
PI	Perform Inspection	Whole fuselage	-
CD	Check if dent is in dent-and-buckle chart	All dents on aircraft	AR application
DVI	Perform detailed visual inspection	New dents, re-assessable dents	AR application
MDD	Measure dent dimensions width and length	Dents in non-critical area	AR application
MD	Measure depth	Dents in non-critical area	-
DDD	Detailed documentation for repair definition	Dents to be repaired, dents close to ADL	3D scan
RD	Repair dent	Dents beyond allowable damage limit (ADL)	-

Some dents on the fuselage take more time to be inspected than others, thus, we denote $m_{i,all}$ as the number of all dents on aircraft i, $m_{i,new}$ the number of dents that need assessment as they are not in the dent-and-buckle chart yet or they need re-assessment, $m_{i,nonc}$ as the number of dents in a non-critical area, $m_{i,cADL}$ as the number of dents that are close to the Allowable Damage Limit (ADL) and therefore need a detailed assessment and $m_{i,bADL}$ as the number of dents beyond ADL that need to be repaired according to the SRM. In particular, it holds:

$$m_{i,bADL} \leq m_{i,cADL} \leq m_{i,nonc} \leq m_{i,new} \leq m_{i,all} \quad \text{for all } i \in \{\text{Aircrafts}\}. \tag{8}$$

Assuming all process steps in Table 3 are conducted by personnel with the same salary s an hour, then, the personnel cost for operational activities for the CINNABAR process $C_{CI,proc}$ can be accumulated as the cost for operational activities $C_{CI,x}$ for process steps x:

$$\begin{aligned} C_{CI,proc} = \sum_{\text{Aircrafts i}} (&C_{CI,PI} + C_{CI,CD} \cdot m_{i,all} + C_{CI,DVI} \cdot m_{i,new} + C_{CI,MDD} \cdot m_{i,nonc} + \\ &+ C_{CI,MD} \cdot m_{i,nonc} + C_{CI,DDD} \cdot m_{i,cADL} + C_{CI,RD} \cdot m_{i,bADL}), \end{aligned} \tag{9}$$

where the cost $C_{CI,x}$ for process step x are calculated as the product of salary s times duration $d_{CI,x}$ of the process step x.
Similarly, the personnel cost for operational activities for the conventional process $C_{co,proc}$ are composed as follows:

$$\begin{aligned} C_{co,proc} = \sum_{\text{Aircrafts i}} (&C_{co,PI} + C_{co,CD} \cdot m_{i,all} + C_{co,DVI} \cdot m_{i,new} + C_{co,MDD} \cdot m_{i,nonc} + \\ &+ C_{co,MD} \cdot m_{i,nonc} + C_{co,DDD} \cdot m_{i,cADL} + C_{co,RD} \cdot m_{i,bADL}). \end{aligned} \tag{10}$$

As the personnel cost for operational activities contribute to both sides of (1), the cost for process steps that are not substituted (PI, MD, RD) can be reduced on both sides. In first user studies [7, 8], with the AR application a reduction of the duration of process steps CD, DVI, MDD within the same order of magnitude was verified. For the 3D scan, a reduction of process duration by an order of magnitude, i.e. from hours to seconds, was observed. This coincides with the findings in [38]. However, as the 3D scanning device is only used for dents close to or beyond the ADL and the AR application is used for all dents on the aircraft, the absolute duration reduction and therefore cost savings depend on both the relative reduction of duration of a process step and the number of dents the process step is conducted on, see inequation (8).

The organizational costs [12] for the CINNABAR process are composed of ongoing organizational cost $C_{orga,ongo,CI}$ (e.g. quality management, process control) as well as cost related to the introduction of the new technology $C_{orga,new}$ (e.g. business process restructuring, change management, disruption).
The ongoing organizational cost $C_{orga,ongo,CI}$ will equal the organizational cost of the conventional process $C_{orga,co}$ and therefore it will be reduced on both sides in (1). For a digitally mature organization it is assumed that new technologies can be integrated easily such that $C_{orga,new}$ is assumed to be of neglectable amount: $C_{orga,new} \approx 0$.

Cost induced by related areas like logistics or planning C_{gene} are assumed to be equal for both the conventional and the CINNABAR process. Therefore, it will be reduced on both sides of (1).

Therefore, filling in equations (2-11) into (1), and reducing equalities on both sides, the cost calculation is

$$C_{CINNABAR} < C_{conventional} \tag{11}$$

$$C_{init,CI} + C_{ongo,CI} + C_{pers,CI} + C_{orga,CI} + C_{gene} < C_{orga,co} + C_{pers,co} + C_{gene} \tag{12}$$

$$C_{init,CI} + C_{ongo,CI} + C_{pers,CI} < C_{pers,co} \tag{13}$$

$$C_{init,CI} + C_{ongo,CI} < C_{pers,co} - C_{pers,CI}. \tag{14}$$

With equation (7), it is deduced that the initial and ongoing technology-related cost must be exceeded by the cost reduction of operational activities of the personnel cost:

$$\begin{aligned} C_{init,CI} + C_{ongo,CI} < \sum_{\text{Aircrafts i}} (&(C_{co,CD} - C_{CI,CD}) \cdot m_{i,all} + (C_{co,DVI} - C_{CI,DVI}) \cdot m_{i,new} + \\ &+ (C_{co,MDD} - C_{CI,MDD}) \cdot m_{i,nonc} + (C_{co,DDD} - C_{CI,DDD}) \cdot m_{i,cADL}) \end{aligned} \tag{15}$$

The parameter influencing inequality 15 are summarized in the following Table 4:

Table 4 – Summary of parameters influencing inequality (15).

Parameter	Description
n_{AR}	Number of AR devices in organization
C_{AR}	Purchase cost of AR device
Prop_{AR}	Proportion of usage of AR device in CINNABAR process in relation to all AR applications
n_{3D}	Number of 3D scanning devices in organization
C_{3D}	Purchase cost of 3D scanning device
Prop_{3D}	Proportion of usage of 3D scanning device in CINNABAR process in relation to all AR applications
$C_{\text{oper, AR}}$	Purchase cost for operating system of AR device
$C_{\text{software CI, AR}}$	Purchase cost for CINNABAR-specific AR software
$C_{\text{oper, 3D}}$	Purchase cost for operating system of 3D scanning device
$C_{\text{software CI, 3D}}$	Purchase cost for CINNABAR-specific 3D scanning software
$C_{\text{update, hw, AR}}$	Cost for maintaining and updating hardware of AR device
$C_{\text{update, hw, 3D}}$	Cost for maintaining and updating hardware of 3D scanning device
$C_{\text{update, sw, dist, AR}}$	Cost for maintaining and updating operating system of AR device
$C_{\text{update, sw, dist, 3D}}$	Cost for maintaining and updating operating system of 3D scanning device
$C_{\text{support, dist, AR}}$	Cost for support for operating system of AR device
$C_{\text{support, dist, 3D}}$	Cost for support for operating system of 3D scanning device
$C_{\text{update, sw, CI, AR}}$	Cost for maintaining and updating CINNABAR-specific software of AR device
$C_{\text{update, sw, CI, 3D}}$	Cost for maintaining and updating CINNABAR-specific software of 3D scanning device
$C_{\text{support, CI, AR}}$	Cost for support for CINNABAR-specific software of AR device
$C_{\text{support, CI, 3D}}$	Cost for support for CINNABAR-specific software of 3D scanning device
$C_{\text{energy, AR}}$	Cost for energy for AR device
$C_{\text{energy, 3D}}$	Cost for energy for 3D scanning device
$m_{i,all}$	Number of all dents on aircraft i
$m_{i,new}$	Number of dents on aircraft i that need (re-)assessment
$m_{i,nonc}$	Number of dents on aircraft i in non-critical area
$m_{i,cADL}$	Number of dents on aircraft i with dimensions close to ADL
$m_{i,bADL}$	Number of dents on aircraft i with dimensions beyond ADL
$C_{CI,x}$	Personnel cost for operational activities during CINNABAR process step x, $x \in \{\text{PI, CD, DVI, MDD, MD, DDD, RD}\}$ as shown in Table 3
$C_{co,x}$	Personnel cost for operational activities during conventional process step x, $x \in \{\text{PI, CD, DVI, MDD, MD, DDD, RD}\}$ as shown in Table 3

4.2.2 Quality assessment

As described in section 4.2, the assessment of qualitative benefits is more challenging than the evaluation of quantitative advantages. According to [51], for the process quality assessment, a set of indicators needs to be identified and evaluated that

- "explicitly address the purpose and process outcomes [...]"
- "demonstrate the achievement of the process attributes [...]" and "process quality levels".

These indicators can be categorized into practices, information items and resources and infrastructure [51]. Hence, for the assessment of the process quality, the purpose and process outcomes need to be defined and corresponding attributes need to be deduced.

The purpose of the dent-and-buckle assessment is the scanning, evaluation including decision-making and documentation of dents in order to guarantee the airworthiness of the aircraft. The measurable attributes for scanning will differ from the attributes of evaluation and documentation: The requirements for dent scanning are extensively deduced in [8]. In addition to general requirements like reliability, integration into workflow, resources, human factors and environmental aspects, they postulate requirements for the scanning system, i.e. the finding and measuring of dents as well as the input into the application. Deduced indicators are localization, measurement accuracy and precision [7, 8]. For the evaluation based on the scanned data, other indicators allow for the quality assessment of the process step, e.g. reliability and reproducibility of decisions based on available information. The documentation quality includes distinct indicators, e.g. the information value, clarity, and fast and unique information acquisition. Additional to such technology-specific indicators for the different purposes, requirements for the process as well as data governance and digital twin are stated as process robustness, damage history and precise communication across stakeholder [6, 7, 8].

Based on these indicators, it is assessed how the different implementation scenarios

- Conventional process: Conventional inspection process as shown in Figure 2.
- AR: Modified inspection process, only AR application implemented
- 3D: Modified inspection process, only 3D scanning device implemented
- Combined: Both the AR application as well as the 3D scanning device are implemented, however as separated tools without integration. This equals the current development stage of the CINNABAR process
- Visible process: This scenario describes an advanced development stage of the CINNABAR process which can be classified into the maturity stage of "visibility" as explained in section 4.1

perform in terms of quality compared to the conventional process as shown in Figure 2. First results are shown in Table 5.

Table 5 – Qualitative process assessment: Quality of technology, process-robustness and data governance.

	Conventional process	AR	3D	Combined	Visible process
Technology-related quality					
Scanning					
Localization	o	++	o	++	++
Measurement accuracy	o	o	++	++	++
Measurement precision	o	o	++	++	++
Evaluation					
Decision reliability	o	o	o	o	++
Decision reproducibility	o	o	o	o	++
Documentation					
Information value	o	+	+	++	++
Clarity	o	+	+	+	+
Fast information acquisition	o	++	+	++	++
Process-related quality					
Process robustness	o	o	o	o	+
Data Governance					
Damage history	o	-	- -	-	++
Precise communication across stakeholder	o	-	+	o	++

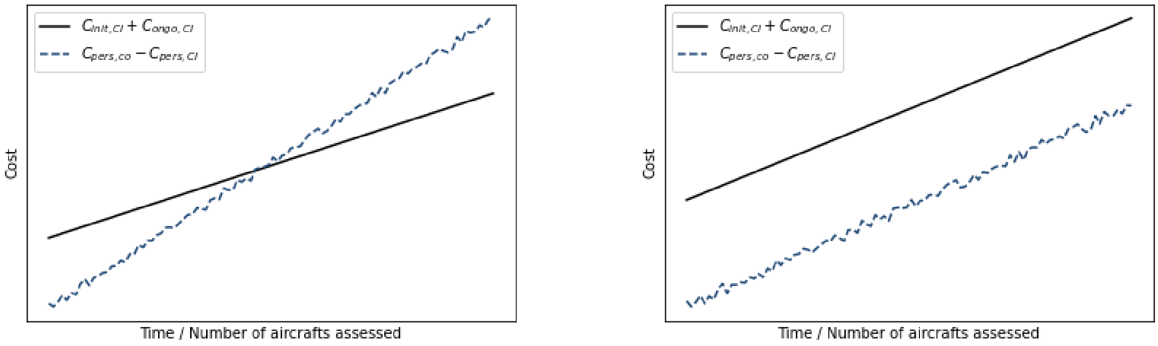
The current conventional process is used as a reference. The assessment is based on the five-point Likert-Skala from "- -" to "++", where "- -" corresponds to a drastic deterioration, "-" a slight deterioration, "o" no significant change, "+" slight improvement and "++" corresponds to a significant improvement in the corresponding indicator. The assessment is based on user studies [8], literature [38] as well as expert interviews.

4.3 Discussion

As described in section 4.1, the implementation of either the 3D scanning device or the AR application classify the CINNABAR process into the communication stage in the digital maturity scale (Table 2), whereas the current implementation of both technologies is classified into the digitization stage, as the two technologies are not yet connected and integrated into each other. This apparent contradiction underlines that a successful digitalization requires not only the development of isolated digital technologies, but also the implementation of interfaces between them in order to realize a holistic and integrated digital organization.

Similarly to the different digital maturity stages of the individual or combined introduction of technologies into the process, also the cost-benefit analyses of the distinct scenarios will differ: The parameters in Table 4 as well as the assumptions leading to estimation (15) are dependent on the organization's size and business model, the chosen AR and 3D scanning device, the available software licences and maintenance contracts as well as the number of dents on the aircraft to be assessed. Therefore, these parameters need to be evaluated specifically for each MRO organization and the expected aircraft to be inspected in order to analyze if the expected economic benefits, i.e. the cost reduction of operational activities of personnel cost exceeds the initial and ongoing technology-related cost. However, as most MRO organizations are on first levels of the digital maturity scale (see Table 2), the prognosis of technology-related cost for the organization depends on high uncertainties. Also, the assumptions about stagnating organizational costs and personnel training and management can only be validated if MRO organizations actually have reached digitally more mature stages in an ex-post assessment.

Thus, as shown in Figure 5, depending on the parameters, the initial and ongoing technology-related cost are exceeded by the reduction of personnel cost for operational activities at various points in time, respectively number of assessed aircrafts.



(a) Scenario 1: Technology-related cost are exceeded by personnel cost reduction.

(b) Scenario 1: Technology-related cost are not exceeded by personnel cost reduction.

Figure 5 – Dependency of cost on parameters.

In addition to financial savings, also a quality increase might justify a process modification [18, 19, 20]. The quality improvements in the process are summarized in Table 5. As described in section 2.2 , these non-monetary benefits might outweigh the financial expenses and therefore justify the implementation. As the conventional process serves as reference, it is classified as "o" in all indicators. When comparing the AR modification with the 3D scanning process, it becomes clear that the two modifications complement each other in terms of scanning technology-related quality. Therefore, when combining both technologies, scanning as well as documentation show high quality improvements. However, as in the current CINNABAR process, no evaluation and decision-making are integrated, no improvement in these fields can be observed. Additionally, the process-related quality as well as data governance stagnate or even deteriorate, as historic damage characteristics are not included in the applications. In a visionary scenario of a digitally more mature CINNABAR process in the visibility stage, an improvement in all sectors is estimated, as the technologies are connected and data provided in the scanning can be automatically evaluated and documented. This improvement underlines the importance of a holistic digitalization instead of only virtualizing individual process steps.

5. Conclusion

In the CINNABAR project, a novel framework for the inspection of dents on aircraft structures has been demonstrated, through the development of an AR application and a 3D scan-based damage assessment [6, 7, 8]. In this publication, these process modifications are classified in terms of digital maturity of the process and corresponding organization as well as the cost and qualitative benefits. With the CINNABAR process, the digital maturity of the conventional process which was classified to be in the hardware compliance stage, was increased to the communication stage for the individual technology implementation. The requirements for reaching the next maturity stage "visibility" have been deduced. Future technology development within the CINNABAR process should be in accordance with these requirements. Additionally, the various cost factors for introducing new technologies into MRO organizations have been deduced from [12] and adapted to the use-case. The assumptions leading to the cost estimation which allows for the calculation of a break-even point need to be validated in further research. Additionally, the economic cost-benefit analysis is dependent on a variety of parameters that need to be quantified in future studies. They can be determined via expert interviews, prognostics in literature as well as the assessment of historic dent inspections. As these parameters may fluctuate between different organizations and aircraft types, sensitivity analyses can be used to identify the determining factors for the cost assessment. As a result, it can be evaluated in which organizational environment the CINNABAR process shows the highest economic benefit. Furthermore, qualitative improvements have been realized with the CINNABAR process. With the ongoing development of the corresponding technologies as well as the implementation of automated decision-making, the qualitative benefits are expected to further increase. When relating the qualitative improvements to the digital maturity it becomes clear that with increasing digital maturity, the quality improves in various aspects. The used five-point Likert-scale can be adjusted in further research such that the different quality aspects can be assessed in more detail. Furthermore, additional quality indicators can be integrated into the qualitative assessment. These qualitative improvements may justify the introduction of new technologies in dent-and-buckle inspection processes. However, in order to compare them with the quantitative monetary values, a quantification of the qualitative indicators needs further research.

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7. Contact Author Email Address

Johanna Aigner received a M.Sc. from Technical University of Munich. She is undertaking research into digitalization and optimization of maintenance processes in aviation at the German Aerospace Center (DLR). mailto: johanna.aigner@dlr.de

Ann-Kathrin Koschlik M.Sc. is a Research Associate at the German Aerospace Center (DLR) at the institute of Maintenance, Repair and Overhaul leading a team of researchers and specialising in Unmanned Aircraft maintenance and predictive maintenance. mailto: ann-kathrin.koschlik@dlr.de

Hendrik Meyer Dipl. Ing and M.BA. is a Research Associate at the DLR since 2014, at the institute of Maintenance, Repair and Overhaul. He is the project leader of the digital twin project DigTwin and the DLR project Digital Twin for Engine components Aircraft Technologies (DigECAT). mailto: hendrik.meyer@dlr.de

8. Copyright Statement

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