DIGITALIZATION AND DATA MANAGEMENT IN AIRCRAFT MAINTENANCE BASED ON THE EXAMPLE OF THE COMPOSITE REPAIR PROCESS

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Abstract

The digital transformation poses a major challenge to the aviation industry with its diverse fields of operations and its mostly historically evolved organizational structure. But there is a lot of potential in the individual organizations for increasing efficiency and reducing obstacles for interoperability by establishing different digitalization concepts.

In the past, research has been conducted on various technologies such as assistance systems, automation or inspection and image processing methodologies in the field of composite repair. However, digitalizing individual process steps using a new technology does not necessarily mean that it will also result in a more efficient overall process. For more efficient processes and the implementation of the vision of a digital twin, the digitalization and consideration of the respective holistic process is necessary. Data consistency, which should run like a thread through all process stages is a key factor and requires a corresponding data management concept.

The repair process for fiber-reinforced composite structures, see Figure 1, is the basis for the development of a vision for a digital transformation in this work. The reason for this is, that the tasks in this process are usually carried out manually. The resulting media disruptions during the technical execution as well as during the final documentation limit the usability of information. This leads to an additional effort for information interpretation during the process execution and inhibits the potential for a data-based learning and improvement process.

In the first part of this paper, the individual process steps are presented according to the current state of the art. This is followed by a process modification doing research regarding suitable technology concepts, which could be used to allow the complete digitalization of the process flow. Based on this, a corresponding data management system for the modified process will is designed, that enables an interaction between the process itself and the digital twin.

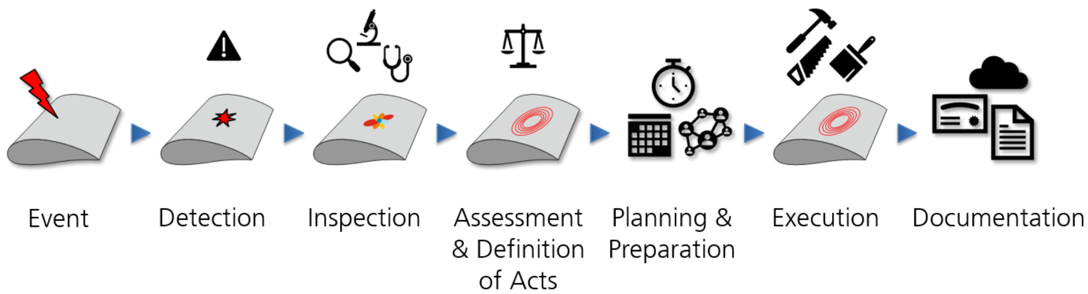

Figure 1: **Overview of the composite repair process steps**

Keywords

Aviation, MRO, Human-Machine-Interaction, Scarf Repair, Composites, Composite Repair, Digital Twin, Maintenance, Repair Process

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ACCRONYMS

ADL .... *Allowable Damage Limit*
AI……………………………….*Artifical Intelligence*
AR .... *Augmented Reality*
DT .... *Digital Twin*
EASA ..... *European Union Aviation Safety Agency*
ERP ....*Enterprise Resource Planning*
FFS ....*Fortschritliche Flugzeug Strukturen*
IoT ....*Internet of Things*
IP. .... *Intellectual property*
IVHM......... *Integrated vehicle health management*
MAREP .... *Maintenance Reported*
MES .... *Manufacturing Execution Systems*
MRO.................*Maintenance Repair and Overhaul Organization*
NDT.................................*Non-Destructive Testing*
OEM.................. *Original Equipment Manufacturer*
PDF ....*Portable Document File*
PIREP ....*Pilot Reported*
PLM.......................*Product Lifecycle Management*
RDL................................*Repairable Damage Limit*
SHM ....*Structural Health Monitoring*
SRM ....*Structural Repair Manual*
UAV................................*Unmanned Aerial Vehicle*
VR .... *Virtual Reality*

1 INTRODUCTION

Currently the aviation industry sector is in a state of change. In the last years, new technologies like mobile internet, IoT (Internet of Things), cloud computing, AI (artificial intelligence) or additive manufacturing enabled the digital transformation in industrial companies around the world. [1] So, to stay competitive and achieve more efficient workflows in the next decades, the aircraft OEM (Original Equipment Manufacturer) and MRO (Maintenance Repair and Overhaul Organization) have to transform their historically grown structures.

Many tasks and processes in aircraft MRO are executed manually and documented on paper. [2] Thus, the traceability of maintenance or factory processes is time-consuming and mostly inefficient. To be more efficient and sustainable in all kinds of services, it is important to integrate the application of new technologies in existing information systems like PLM (product lifecycle management), ERP (enterprise resource planning) or MES (manufacturing execution systems) etc. Only if digital technologies “written above” are fully implemented and structured in a network, the interaction between real-world objects and virtual ones (digital twins) will be enabled. [3] To achieve the greatest benefit from DTs (digital twin) or data-driven processes, a wide data compatibility, suitable interfaces and a stakeholder-neutral and independent setup are key requirements. [3]

In some cases, only one sub-process is investigated to increase the efficiency of a whole process flow. One example for this is, a new technology, like a scanning system, that can make the sub-process faster and create some output e.g. pictures, point clouds etc. But that, does not necessarily make the whole process more efficient. If only one process step creates additional output in the form of digital data, the data can not be shared or used in other processes. For a meaningful digital transformation, a holistic view of processes and organizations is necessary.

In this paper, the manual scarf repair process of fiber reinforced composite structures is used as an example for using new technologies to create a vision of a digital transformation. The importance of cooperation between the individual stakeholders should also be shown.

2 PROCESS RELATED STAKEHOLDER

The stakeholder for modern repair processes, can be seen as the stakeholder of integrated vehicle health management (IVHM). In [4], [5] the main stakeholders for an integrated vehicle health management system were identified. The operator is the operator of the asset. He usually owns the asset and makes the operational decisions. The owner is the owner of the asset. He can be the operator at the same time. But he can also be the lessor or a parts pooling company, for example. The maintenance organization, in the following shortened as MRO, repairs either the asset, the component or the sub-component. Several MROs can be involved in a repair of a component. For example, MRO 1 dismantles the component from the asset. MRO 2 repairs the component and breaks it down into sub-components and MRO 3 repairs the sub-components. However, if the respective authorizations are available, all work can take place at a single MRO.

The OEM is the manufacturer. Here the subdivision applies similarly as to the MRO. There is a manufacturer for the asset (or system integrator), one for the component and one for the sub-component. But there can also be an OEM that covers several levels. [6] The process interaction of the relevant stakeholder can be found in Figure 4.

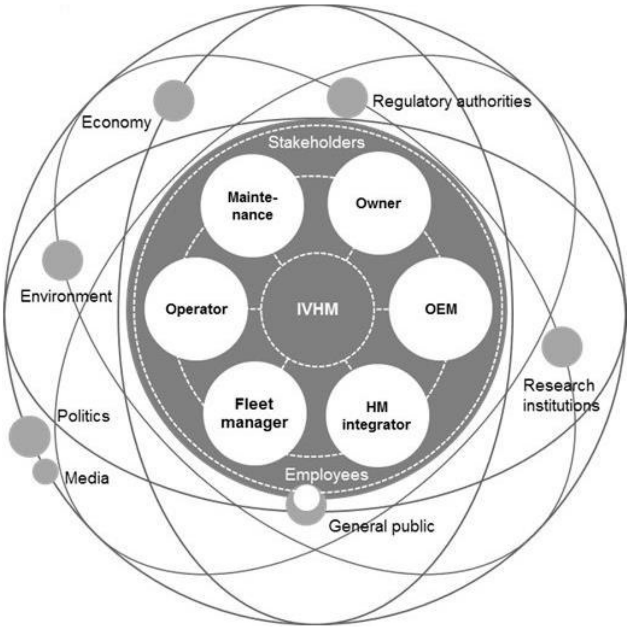

Figure 2: Stakeholder IVHM [4]

3 CONVENTIONAL SCARF REPAIR PROCESS

The conventional repair process for composite aircraft structures is carried out with a high amount of manual tasks. At this point, the main steps of the conventional process are explained in more detail. Each step can be divided into 3 main areas – Preparation, Execution and Close-up as shown in Figure 3.

Figure 3: General Process

In the preparation step, the relevant documentation needs to be identified, prepared and distributed. This includes aircraft manuals, task cards and job cards. The execution step includes all activities performed by the maintenance staff on the respective part or aircraft. During the close-up, the clean-up of the workspace and the documentation takes place. Especially in aviation the documentation is a major task.

The first step in a conventional composite repair is the visual inspection of the aircraft. The damage detection can be carried out as unscheduled maintenance by a pilot (PIREP) or by maintenance personnel (MAREP). Alternatively, the damage can also be identified during scheduled maintenance, in particular as part of a zonal inspection or a maintenance task assigned to the component. For example, spoilers have to be checked for surface damage every 12 years. [7] A main problem of visual inspection is, that many damages are hard to find with the bare eye and are often greater than can be seen from outside. In addition, a visual check-up that ties up resources from different units is cost-intensive and time-consuming. For a full aircraft inspection, it can take days for preparation, execution and close-up processes. [8]

In this paper, we focus the overview (ref. to Figure 4) on the process steps beginning after the damaged area has been detected and the specific component has been dismantled.

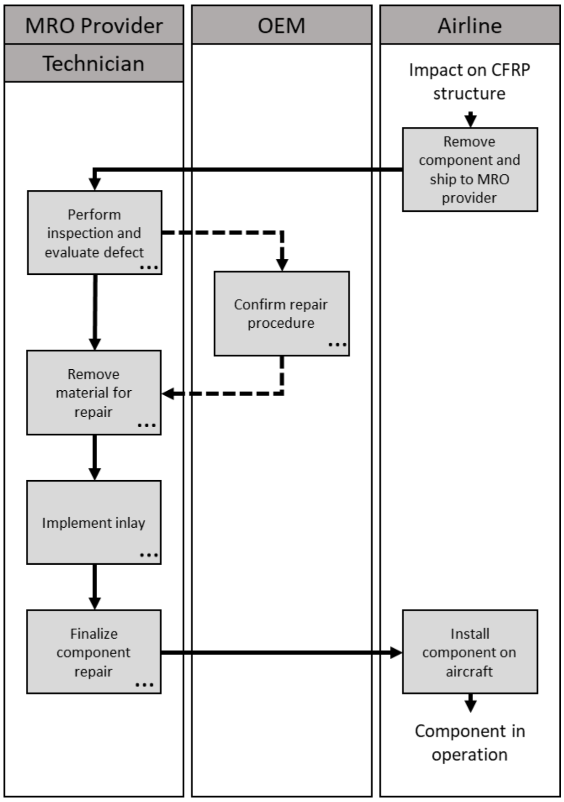

Figure 4: Overall process and interaction between stakeholder for repairing a carbon fiber component [9], [10]

The NDT (non-destructive testing) inspection is the first step to get more information about the damaged area. The most common inspection method for that is the ultrasonic scan. For the preparation, the technician has to collect all necessary documents, materials and measurement tools. After that, the measurement devices must be calibrated for the current component configuration (e.g. material thickness etc.) and the surface must be prepared in order to perform the ultrasonic scans.

For analyzing the damaged area, the technician manually scans the surface with the ultrasonic sensor to check if there are any irregularities in the sensor signal. If the technician finds any defects in the component structure, he marks the damaged area with a pen directly on the surface. Finally, in the close-up block, the technician completes the final report of the inspection. This report contains information about the inspection procedures, the kind of tools and materials that were used during the tests, the calibration setup, the damage size and position, photos etc. Most of this information documented in paper form or typed manually into a template. For instance, the damage size and its position are transferred by hand to a transparent film. To ensure a better orientation, important reference points or geometries are added to the sketch. Later on, in the office, the technician scans the film in order to transfer the sketch into a Word or PDF (portable document file) document.

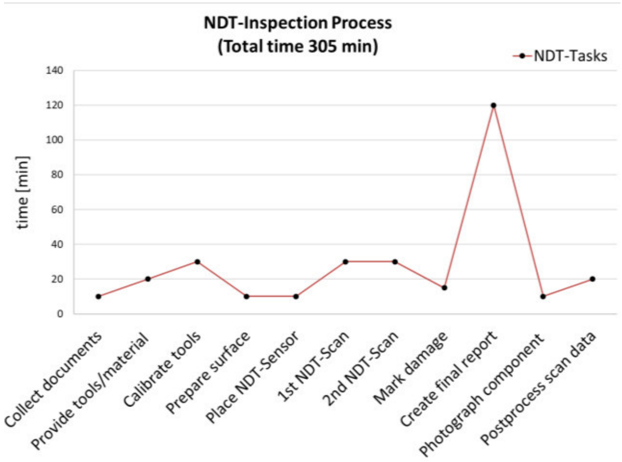

Figure 5: Process times during ultrasonic testing [11]

The diagram in Figure 5 shows the time for each process step of the ultrasonic test procedure during a pilot test. This process analysis was carried out in the context of the project FFS 7. [11] It should be noted that in this example 69 % of the time is spent on preparation and documentation.

Based on the results of the damage inspection, the damage assessment is performed. For every component of an aircraft, the OEM describes type-specific decision-making processes in the SRMs (Structural Repair Manuals). [9] With these documents the technician can specify the current damage type regarding damage size, position and component characteristic. Two possible cases are considered here in order to define the further repair process. Either the damage is within the limits of the ADL (Allowable Damage Limit), which is specified for different zones of the component, or the damage is categorized as a non-allowable damage. [12] “Any damage beyond the RDL (Repairable Damage Limit) is not covered by the SRMs”. [9, p. 5 Dienel] In this case, it requires the OEM support.

During the whole maintenance process, the responsible organizations have to plan their processes in order to get the component ready to fly again as soon as possible to keep the costs as low as possible. Due to the lack of digitalization in many areas, it is hard to transfer the data out of the documents of the previous process steps. The same also applies to the complete maintenance history of the respective component. For example, sometimes an already repaired damage area is detected after carrying out the damage inspection/assessment and removing the paint from the component surface. In this case, it must be checked again whether a repair is possible at all. If so, the repair process, material procurement and resource planning have to be adjusted.

As just mentioned in the example, in order to make the underlying composite structure accessible, the paint layer of the component must be removed for the pending repair. Once the paint is removed, the repair execution can start. The repair process includes a large number of individual steps regarding preparation, execution and documentation. Therefore, only the main points are described here. At first, the technician removes the damaged layers of the composite structure and creates the scarf contour, shown in Figure 6, with a hand-guided grinding tool. This procedure is also implemented in the SRM for the specific component. Before the scarf process can start, the technician has to plan the scarf contour according to the present damage size. Depending on the scarf geometry, a template might be used to mark the reference contour on the surface. Through education and years of experience, a technician can evaluate the work status during the grinding. However, a certain inaccuracy remains due to the manual execution, since there is no other geometric check of the final contour. Also, a constant transfer of the final contour to support the manual grinding process is difficult too.

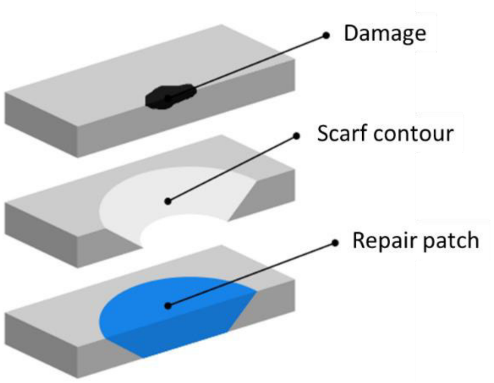

Figure 6: Scarf repair procedure [13]

Once the final scarf geometry is created, the rebuilding of the removed area can begin by adhering the composite layers step by step. Beforehand the repair material has to be ordered and forwarded to the respective workplace. Then, the fiber material must be cut out for the individual layers according to the scarf contour.

At the end of the final repair, the NDT experts scan the repaired structure again to rule out any irregularities in the repaired structure. [11] All the specific workflows must be documented manually and stored in various database systems of the respective stakeholder, in this case the MRO company.

Despite this amount of documentation, there is too little exchange of information between the individual stakeholders to enable more efficient processes. The “data” transferred between the stakeholders is limited to administrative data like purchase orders and billing information or the aviation regulation-based information that is needed for certificates like the EASA Form 1. Most of the information and data generated in a process step stays in the respective stakeholder organization. In order to implement more efficient workflows, a greater use of digital technologies for supporting the operators, data acquisition, data storage and distribution across all stakeholder boundaries is required. Therefore, in the next chapter we present different technologies and a data management concept for such a transformation.

4 MODIFICATION TROUGH DIGITALIZATION

In order to derive the greatest possible benefit from digitalization measures, data management is necessary across the entire digitalization process. The overall process begins with the damage detection and ends with the documentation. As the general repair process steps are given by the physical repair steps, the high-level process (ref. to Figure 4) is not modified. The following process description shows different technologies for the different process steps and the expected output data of these steps.

In the following description we assume that the digitalized process has already been run through several times and the digital thread for the component is completely available. Within the DLR internal project DigTwin the digital thread was defined as:

> *“The digital thread is a concept that represents a chronological storage of information and data for one or more physical or logical objects across product life cycles. The concept realizes a single source of truth and allows complete traceability of any data of the entire life cycle"* [3]

For an ideal digital process flow, the following digital data / models should be available:

- Composite Design (Layers, Materials)
- Repair procedures
- Finite Element Method (FEM) Simulations
- Material properties
- Damage / Repair History

Some of the information is available to the MRO in the form of the SRM. Other information is only available to the design organization, such as the FEM calculations. Therefore, it makes sense to separate between data, which would be part of the digital twin and models and application, which would be part of the application layer (ref. to. [3]) of a digital twin.

In the following, the individual process steps are briefly described and the possible outputs are listed. It should be mentioned, that these tables are by no means exhaustive. Also, the format of the variables is not determined. It is also very likely, that on productive systems some of the parameters would be new classes as well.

When detecting damage, the following information should be transmitted digitally. This includes at first the information about the part itself which are shown in Figure 7.

Part
Part_id
Partnumber
Name
Serialnumber
Installation Location
...

Figure 7: Output - Part table

The damage table (ref. to Figure 8) will be transferred together with the part information from the detecting stakeholder (most likely in the responsibility of the operator). Depending on the digitalization level the parameter of this table will be filled automatically or manually and is limited to the available parameters. With the use of AR/VR and the projection of the repair history onto the part an early repair decision could be made. [14]

Damage
Damage_id
Part_id
Damage type
Date
Time
Damage Size
Repairable
Damage Location
Damage geometry
...

Figure 8: Output - Damage table

Modern SHM (Structural Health Monitoring) can detect damages, without dedicated maintenance tasks. In [15], [16] a guided waves SHM system for complex composite structures is presented including the performance of detecting the damage location and size in these structures. If such a system is used, the system should transfer the detection information with additional information to the above given data:

- Damage Location
- Damage Size

Also, UAV (unmanned aerial vehicles) can support a visual inspection. A drone-based inspection can detect and classify a wide range of defect types in a significantly shorter time and can reduce safety incidents during conventional inspections. Such a system can be important to support younger inspectors during damage characterization. [8] Furthermore, artificial intelligence (AI) image analysis could be used to extract the above-mentioned data [17]. Also, through the use of damage databases, similar damages can be identified with the help of artificial intelligence. [18]

Using a damage database, resources such as man-hours, material costs, machine times and throughput times (ref. to Figure 9) can then be planned in the first process step on the basis of statistical data. In the case of a complete digital thread, a decision can already be made at this point in time as to whether the component can be repaired or scrapped if, for example, the component has reached a maximum number of repairs. [19]

Process forecast
Damage_id
process_forecast_id
process_id
expected material
expected man hours
expected turn around time
expected cost
...

Figure 9: Output - Process forecast table

When the first information about the damaged area is available, an initial damage assessment takes place in process. During the damage evaluation, a visual inspection of the component is carried out. For damages resulting in deformations different scan technologies are available. [20] In particular, the location of the damage and the size of the damage are decisive. Deep learning approaches for visual inspections are developed [21].

The outputs are:

- Damage position
- Size of damage
- Repairable

If these outputs are already available in the damage table (Figure 8) the values are updated during this process step. Otherwise the values are set for the first time. With the updated values, the planning is executed and the values of the process forecast table (Figure 9) are updated.

The next steps take place in the part of the detailed damage analysis and assessment:

- Damage analysis
- Repair analysis
- Repair design

In the further damage analysis, the exact size and type of damage (multi-layer defect, single-layer defect, core defect, etc.) is determined with the help of NDT methods. Regarding the use of digital tools for this step, conventional NDT could be combined with a marker-less tracking technology. In [22], it is shown that an ultrasonic sensor as well as the component can be tracked and the NDT data recorded directly with the sensor position and orientation. In [23] an automated task sequence for a fully automated analysis of ultrasonic data is presented. So, the manual marking process and documentation of the conventional NDT process, as described in chapter 3, would be obsolete and all data could be stored digitally. The following data should be transmitted:

- Type of damage
- Size of damage
- Damage Position
- Damage geometry

If these values are already in the damage table, the values will be updated and the planning algorithms will run again, to update the forecast table.

Additionally, with the data from a digital NDT the decision-making process for a suitable repair planning and repair method could be supported. For instance, instead of the damage size, the residual strength of the composite structure could be used as an additional factor for evaluating the repair design and execution process. [9]

In the repair analysis, with the information from the damage analysis together with the possible repair methods, the decision about the repair method is made. In addition to the data from the current process steps, this also includes information about the repair process.

Repair
Repair_id Damage_id Part_id
Date Time Repair type Repair size Repair location Repair geometrie SRM compliance OEM approval Residual strength calc. ...

Figure 10: Output - Repair table

Also, the repair geometry is defined in this process step and filled in the respective tables. With these starting values, material could be made available for the repair process in the short term, since prepreg material is normally stored in a frozen state.

The output variables are the repair process parameter (ref. to Figure 11) and an update of the repair table (ref. to Figure 10).

Repair process
Repair_process_id Repair_id Damage_id Part_id
cutout size sharpening angle curing cycle (to be) repair cost (to be) ...

Figure 11: Repair process

The next step is optional, or needed if the repair is not a standard SRM procedure. In the repair verification, the success of the repair is proven, for example, by determining the residual strength using FEM. [9] In commercial aviation operations, this can be done by simple stiffness calculations of the MRO, which is then approved by the design organization (OEM). Alternatively, the design interpretation and calculation are carried out by the design organization. Therefore, the damage related parameters need to be transferred (Figure 7, Figure 8). The output variables are filled in the two repair related tables (Figure 10, Figure 11).

For the task execution of the material removal there are several technologies from assistance systems [24], [20] and semi-automated systems [13] to robotic task execution [25].The main input variables come from the repair design process step.

In addition to support during the grinding process, there is also the option of outputting and further processing the final geometry. The individual layers of the repair can be calculated from this information and automatically transmitted to a plycutter. This means that the individual repair layers can be manufactured directly. This digitalization step was particularly emphasized by the employees of the composite repair shop during this project. The repair build-up can also be used to calculate the curing cycle. The data, that arises during the repair process should all be fed into the digital thread. This includes:

- Process times (AS-IS)
- Material used (batch, part number, ...)
- Tool used
- Repair structure (AS-IS)

The quality check can be done in different ways. On the one hand, a test bond can be checked for durability. Alternatively, the repair itself can be checked for defects (air inclusions, matrix defects, layer defects) using NDT methods. At the same time, a deviation analysis between the AS-IS and TO-BE values can be carried out in the case of digitalized processes with the following output:

- Proof of quality
- If necessary, NDT data

The documentation in the digitalized repair process takes place via the digital twin of the component. In addition, the “Form 1” or “Release to Service” required in aviation is be issued. Filling out the documentation can be largely automated thanks to the digital pre-processes. When storing the data, the data integrity must be guaranteed at all times. There are several approaches also for certification and documentation based on blockchain methodology. [26]

When the part is installed in an aircraft, the digital part also needs to be installed in the digital twin of the aircraft, to enable the possibility of data usage over the life cycle of the aircraft.

5 DIGITAL TWIN FOR COMPOSITE PART REPAIR

Since on legacy aircraft most of the composite parts are used for secondary structures, the part can be separated from the aircraft and installed on another aircraft after repair. Therefore, the digital twin needs to be modular, to allow the integration of new parts and the removable of damaged parts. This could be established by a hierarchical digital twin for different level. On the top level, the digital twin of the aircraft for all parts, which stay on the airframe for the lifecycle. The next level is for line-replaceable components, were a digital twin is beneficial. As an example, this could be composite parts like flight controls, but also landing gear, engines or air condition components. Depending on the system complexity several further hierarchical level could follow (ref. to Figure 12).

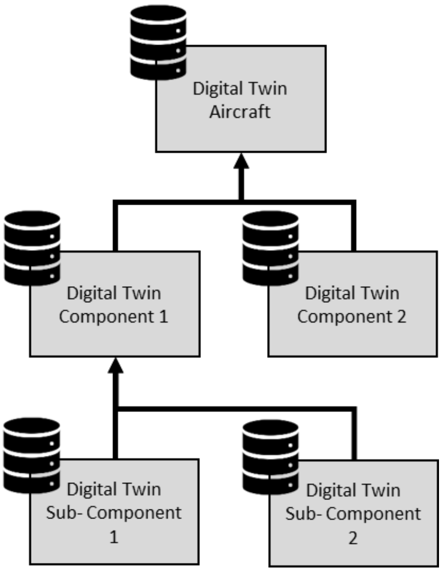

Figure 12: Digital twin hierarchy

It is possible that the life cycle of a part is different to the life cycle of the aircraft. During the life cycle of a part it may switch from one operator to another.

This leads to the need of a cross-stakeholder digital twin concept for high value assets, which have a different life thread compared to the next higher asset.

On the other side within a digital twin, different data, which needs to be protected, are included. Therefore, such a system needs an IP (intellectual property) protection for designs, data and models.

In general, two different architectures could be used for the digital twin. On one side, the centralized digital twin, were all stakeholders need to integrate their data. This digital twin could be located at an involved stakeholder or at an independent service provider. All other partners in the value chain would be "forced" to provide their data to this digital twin. This could lead to an advantage for the data holder over another stakeholder. In aviation several digital twin approaches owned by one stakeholder like Aviatar [27] or Skywise [28] can be found. In Figure 13 this architecture is shown with the example of an OEM as the digital twin provider. The airline and MRO provider need to transfer the data to the OEM. Therefore, the OEM has a knowledge advantage over the MRO provider and the airline. Especially for the development of digital services the overall access to the data is beneficial.

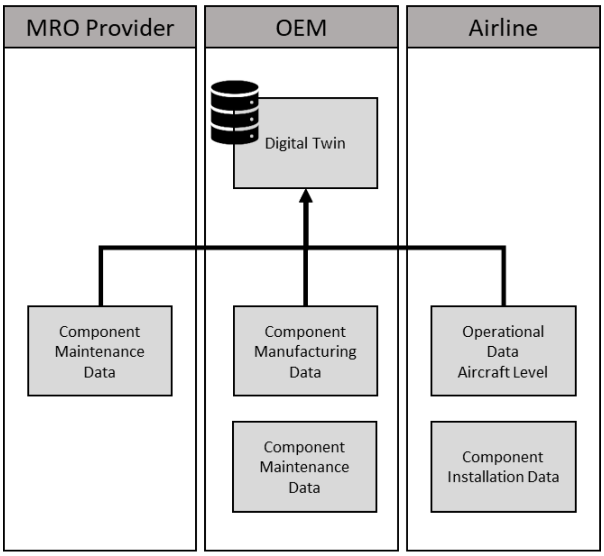

Figure 13: Centralized digital twin

On the other side, a distributed system could be a solution. In this case, each stakeholder holds their own data. This would enable the stakeholders to integrate all their data into the digital twin, even if the data is relevant for the business model of the company. Data access would be completely under the control of the data owner and can be granted to others as a standard deliverable alongside other services or as an independent product. The data exchange between the different data bases need to be defined by developing interfaces, access rights and standards. Especially the interaction between the digital twins need to be regulated, as only the stakeholder with a legitimate interest should have access to the data needed for the services and products associated with the part. The digital Twin itself arises from the network of all the data models. One possible solution could be the approach of Industry 4.0, which uses the digital twin as a system, which is referring to the different data [29]. Also, first standards for data classes can be found for example by the ECLASS foundation [30].

Especially for the aviation ecosystem the standardization is one of the most important things. As commercial aviation is a duopoly divided by imperial and metric systems, the standardization is needed even to choose the reference system. As an example, for the standardization of the damage location, not only the unit is needed, but also the reference coordination system and the direction of view. Even for the damage_ID a lot of standardization is needed, if this ID is used as a reference between multiple stakeholders, to enable the identifiability to a unique damage data set over the whole ecosystem.

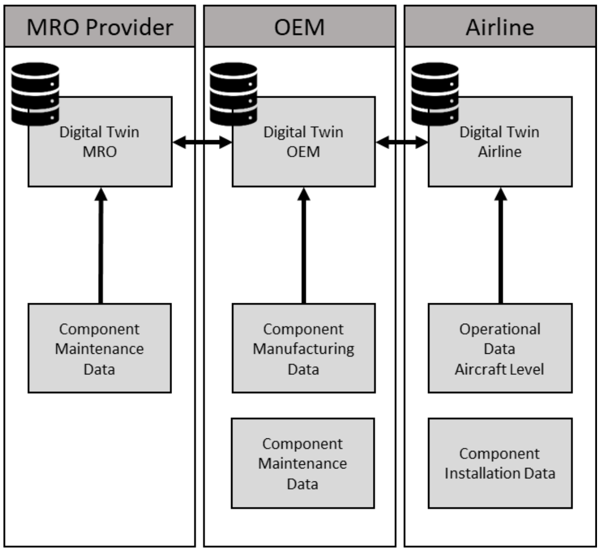

Figure 14: De-centralized digital twin

6 CONCLUSION

The actual digitalization in repair processes in aviation maintenance is very limited at the moment. But there are many different research initiatives for the digitalization of single tasks and technologies. The literature review shows, that for each process step several technologies are under investigation.

To enable the full benefit of these technologies the component needs a digital twin. This DT architecture needs to work across stakeholder borders, to integrate the information, data and models from the different partners. Therefore, a distributed digital twin system is needed. This will require a high level of standardization, to enable the interaction in the aviation ecosystem. Also, the access to the data must be controlled, to protect business models on one side and enable new digital services on the other side.

Within FFS7 the repair process was performed, to generate all relevant data. Within FFS8 it is planned, to set up the proposed data model to evaluated the digital twin approach for this specific use case.

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