DIGITALIZATION OF REPAIR PROCESSES IN AVIATION: PROCESS MAPPING, MODELLING AND ANALYSIS FOR COMPOSITE STRUCTURES

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Abstract

Maintenance processes in aviation are of significant importance in order to ensure the operational readiness comprising the availability and reliability of aircraft. The increasing operation of composite-intensive aircraft including Airbus A350 or Boeing 787 as well as the growing usage of composites in secondary structures like stabilizers and winglets motivate research in modification and optimization of repair processes for composite structures in aviation. At the moment, the repair of composite structures is characterized by manual task execution, documentation in paper format and the focus on individual steps. In the future, the process should be digitally supported, documented in paperless format and the focus should be on the interactions and interfaces of the individual process steps in order to optimize the repair process. This is the first important step towards data storage and provision for more automated task execution and decision support systems. This then may serve as a basis for a visionary repair planning and process execution which is highly automated with perfectly aligned and interacting sub-processes with its documentation taking place completely in the digital world. In this paper, the literature and industrial solutions for digital support systems and process modelling approaches for both the aviation sector as well as other industries are reviewed and compared with respect to their digitalization level. The state-of-the-art repair process of aviation composite structures is mapped using the example of sharklets together with an industrial partner. This model is realized using the event-driven process chain (EPC) notation in the simulation software ARIS. The overall process in the repair shop is described hierarchically and relevant documents, information and data are identified. The different process steps are analyzed and potentials for a modified process execution are shown.

Keywords
Aviation; Maintenance; Digitalization; Process mapping

1. INTRODUCTION

The airworthiness and availabiilty of aircraft are two major priorities of aviation and they rely heavily on the regular execution of maintenance, repair and overhaul (MRO) tasks. With the growing fleet size also the global MRO market is predicted to grow within the next decade: Starting from $77 billion in 2022, the market is expected to reach $125 billion in 2023, corresponding to an annual grow rate of 2.9% [1]. According to this report, the Covid-19 pandemic as well as the Russian war against Ukraine amplified already existing bottlenecks along the MRO process chains such as labor shortages and supply chain disruptions. With the introduction of the composite-intensive Boeing 787 in 2011 or Airbus A350 in 2015 as well as with the growing usage of composites for secondary structures, the MRO processes of these composite structures will increase as well. The repair process of carbon-fibre reinforced plastics (CFRP) needs to meet high demands on the structural integrity of the parts. As the process is quite complex and highly individual, standardizing the process is quite tough. The tasks are mainly executed manually and the work is documented in paper format. As there is no consistent data stream, the focus lies on the individual process steps. Hence, current research also focuses a lot on the digitalization and automation of the individual process steps rather than on the interfaces between them and the whole process chain. However, it is evident that the consideration of the overall process chain is necessary to provide a more efficient process and the basis for a digitalized process [2]. In their publication, the scarfing repair process of a composite structure is used as a use case. The overall process consists of the steps shown in FIG 1.

This process serves as basis for the modeled process in this paper: In the following, an overview of digital support systems and process modelling approaches is provided, before the actual repair process is described. First, the modeling methodology is explained and then, the state-of-the-art repair process of aviation composite structures is modeled and analyzed.

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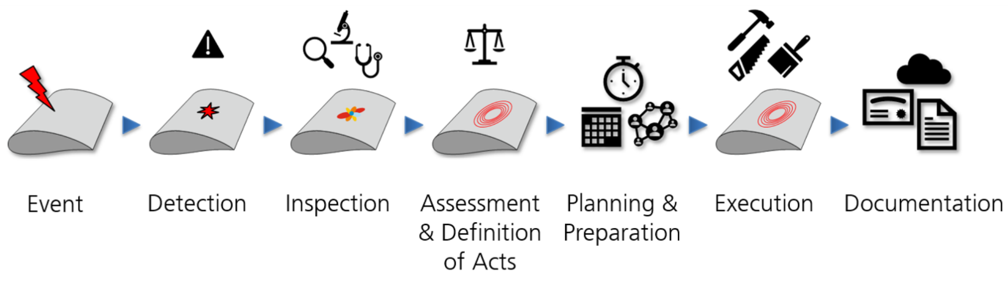


FIG 1. Overview of the composite repair process steps [2].

Possible modifications and their potentials are outlined.

2. BACKGROUND: DIGITAL SUPPORT SYSTEMS AND PROCESS MODELLING APPROACHES

The digitalization progresses in a variety of industries and sectors. In the following, an overview of digital support systems and process modelling approaches is given, first without restriction to one industry. This is followed by digital approaches in the aviation maintenance sector. At the end of this section, the digitalization of the aviation maintenance sector is compared with the state-of-the-art in other industries.

Digital tools are designed and used in different sectors in order to improve business. The actual benefits of digital business solutions depend, however, strongly on the region the business is located, the industrial sector and the firm size [3]. Small and medium-sized enterprises are usually characterized by high variety and low-volume [4], and for regular modifications in the processes, static digital tools are obsolete, whereas adaptable models are required [5], [6]. Also, digitalization has to be a holistic process including the whole value creation from planning to finishing the production [7]. It cannot only be realized for specific IT solutions, but need to integrate information across a variety of IT systems. As methods and processes are intrinsicly different for various industries, the disciplines think in their "discipline-oriented silos". To overcome the solution-making in these silos Sysem Lifecycle Management as "holistic information and process management" is introduced [7].
Another approach to assess scenarios of interacting processes is simulation modeling [8]. With the model, bottlenecks like idle times can be identified. Another technology used in the context of Industry 4.0 are cyber-physical systems [9]. Physical processes are digitally represented in cyber-physical systems and effectively optimized such that autonomy and flexibility may increase and the processes are more customized. Especially for intra-logistics, the use of cyber-physical systems may be beneficial. Also, digital twins may be used for logistics, although they are more advanced regarding manufacturing processes [9].
Recently, the use of digital twins is increasing in production logistic activities as well [10].
Digital decision support systems may be used for the optimization of shop floor activities [11] as well as the process planning and management of personnel and other ressources [12].
For the implementation of such systems, structured data is essential. It can be realized via digital data management, which is particularly increasingly important in the context of Internet of Things (IoT), computing Edge devices, Cloud computing, artificial intelligence (AI) [13]. This comes along with data visualization tools like augmented reality or image recognition tools. With data management also automated process execution can be enabled [14].
For introducing new technologies, the involved stakeholders have to be considered. Therefore, [15] et al. conducted a stakeholder analysis for digital twins for battery systems. They identify five ways a stakeholder may be linked to the digital twin, either as functional input or output, or because of finanical, legal or public interest.

Aviation maintenance is like maintenance in general not as digitalized as other industries. However, it is assumed that "Digitalization could be the most sustainable approach towards maintenance services, and this is yet to be understood" [16]. Whereas in the literature, there are publications about digitalized maintenance services they seem to not have found entrance in the industry yet [17]. A trend to data-driven maintenance could be observed in the last years, especially for planned maintenance [18], [19]. In [17], the term of e-maintenance is cited as to focus on "processing, integration and distribution of information to support decision processes" [20]. The term "e-maintenance" was common in the literature of the 2000s. However, there is no unique definition for the "e" in it. Some refer to it as abbreviation of "excellent", others as "efficient", "effective" or "enterprise". E-maintenance solutions for the aerospace sector are explored in [21] against the background of limited information access and understanding because of the variety of involved stakeholders [22]. For realizing better predictions and process planning,

the heterogeneity of data formats and limited access to information needs to be overcome. One approach for data integration is the use of ontologies [23]. Ontologies allow for representing domain knowledge and reasoning via semantic relations. The authors claim an "apparent lack of ontologies for aircraft maintenance records domain", although it was shown that their use in aviation increased in general [23].
A possible explanation is the low level of digitalization in the aviation maintenance domain.
To overcome paper-based, often non-structured information (manual process execution and hand-written documentation), a holistic ontology-based solution for process execution and involved reports is developed [24].
While a lot of literature focuses on keeping the airworthiness of an aircraft, only a few focus on repairing components and hence, re-establishing the airworthiness of defect parts, e.g. [25]. Ontologies may also be used for the reengineering of MRO Processes [26].
One difficulty in MRO processes is the attached logistics, e.g. supply of material from other suppliers like spare parts. For their punctual delivery, a functioning spare parts tracking management system needs to be used. In [27] a blockchain-based system for supporting this logistic task is presented. The blockchain philosophy guarantees secure transactions and interactions between various stakeholders.
Another digital support system which has gained a lot of attention in aviation maintenance is the digital twin. First approaches could be traced back to the 1970s with the introduction of a physical twin [28], [29].
In the maintenance sector, digital twins are used for the transition from "post-event maintenance" to "predictive maintenance". The condition of an aircraft can be monitored via integrated vehicle health management combined with the digital twin of the aircraft [29].
A lot of scientific research addresses the use of digital twins for individual process steps along the MRO process chain, e.g. [30]. The concept, however, is also usable for the whole process chain [31]. They use the digital twin for a decision support system for individual regeneration processes. Due to their individuality, the decisions are mostly experience-based and individually fitted to the problem. The authors' goal is to allow for a data-driven decision support.

Compared to other industries, the aviation maintenance sector lacks a degree of digitalization. Different approaches reach from e-maintenance concepts through ontology- or blockchain-based technologies to the concept of digital twins. Process models and decision support systems in this area do exist, however rather for optimizing plannable events like scheduled maintenance, fleet management or supply chain management. There are different possible explanations for their low occurence in repair processes:

- Repair processes in aviation are highly individual, as there is a variety of possible damage causes and therefore, there are a lot of damage types which need different repair strategies. Due to this variety, nearly each process is individual which complicates the standardization the repair process.
- In repair processes, a variety of stakeholders is involved: The operator of the aircraft, the MRO who conducts the repair and the OEM who owns relevant design data like FE- or CAD-models. As each stakeholder has different interests, the exchange of relevant data is often not easily realizable.
- Different stakeholders, but also different departments within one organization use different tools such that the created data does not follow any standard. Therefore, the output data of one process step is often not directly usable as input for the following process steps.

3. METHODOLOGY

In order to renew the aviation repair process of CFRP structures, the current process is mapped and analyzed. This analysis identifies potentials of modifying the current process.

3.1. Process mapping

In the following, the modelling notation and software used for the mapping will be explained. The need for a hierarchical description is shown.

3.1.1. Modelling notation and software

ARIS

ARIS is both a concept and a software tool. ARIS is an acronym for *Architektur integrierter Informationssysteme* (Architecture of integrated information systems). The ARIS concept was developed by August-Wilhelm Scheer in the 1990s and serves as a framework for companies to describe their business. The framework describes processes with five different *description views*: The function view, organization view, data view, product/service view and process view. Each of these views consists of the three *description levels* concept, data concept and implementation (see FIG 2).
For each of the description views, the ARIS software offers various *model types* such as organigram, BPMN, EPC and many more. [32] Hence, the ARIS software tools allows for process modelling with conventional modelling notations, but with respecting the different description views.

Event-Driven Process Chain

The Event-Driven Process Chain as a process modeling language represents acitivities in a business process. It is the "central method for the conceptual integration of the functional, organizational, data, and output perspective in information systems design" [33]. The *function* elements represent activities and *event* elements represent prerequisites and results of fun-

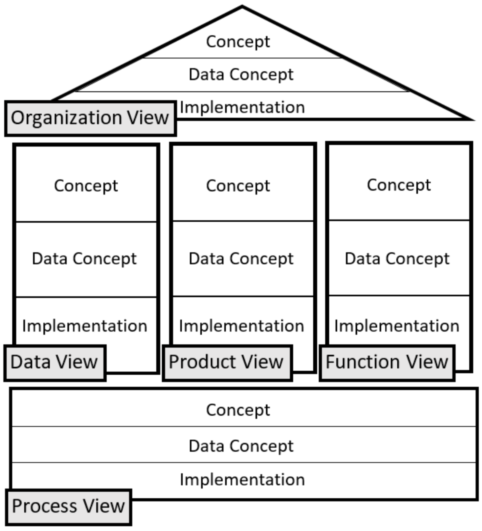


FIG 2. Visualization of the ARIS concept: ARIS House.

tions. Both element types may be connected by three different *connector* types: AND, OR and XOR, the last being the exclusive or (see FIG 3).

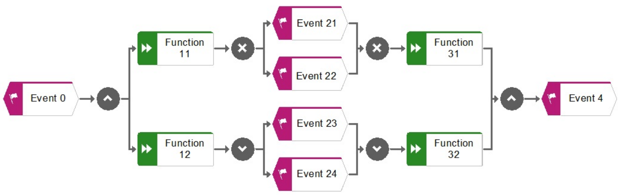


FIG 3. Example: Event-driven Process Chain (EPC).

It is suggested to alternate between function and event elements, however, for linear processes, also a sequence of functions without inserted events is possible [32].

3.1.2. Hierarchical description of repair process

The repair process of CFRP aviation structures may be mapped in various degrees of detail, depending on the purpose of the process model. For the airliner who sends the damaged part to the repair shop, only the top level process REPAIR consisting of the three steps Send part to repair shop, Repair, Receive repaired part and corresponding documents is of interest. For an overview of the different steps a more detailed description of the process steps is necessary. For the mechanic who has to perform, e.g., the inspection, however, the process step Inspection is not detailed enough, but he needs more information on the individual tasks. The approach of modeling the process on the most detailed level possiblle leads to a complex and unclear picture of the overall process. This is remedied by describing the process hierarchically. This is realized by using *process interfaces* in the ARIS software tool: The *function* element of a superordinate process is substituted by a process interface. This process interface links to the subordinate process with more detail without making the superordinate process too complex.

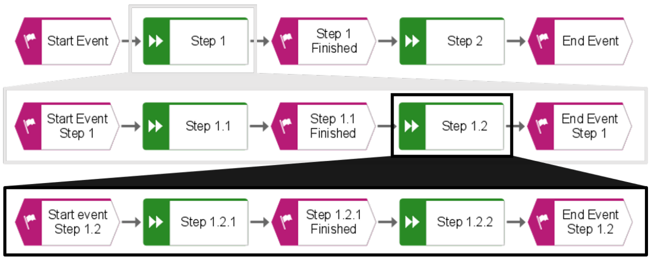


FIG 4. Hierarchical Process Description: A process step may be a process itself.

3.2. Process analysis

The mapped process is analyzed with respect to the processing times of the different process steps. First, the analysis is conducted on the top level to show the distribution of times along the whole process chain. The analysis on more detailed degree is conducted for exemplary process steps. In the analysis, two different durations are used: The *turnaround time* (TAT) and the *working time* (WT). The WT of a process is the time that people work on this process. The TAT of a process is the time between the start point and the end point of this process. It can be longer than the WT, if e.g. waiting time is included, but it may also be shorter than the WT, if e.g. two persons work in parallel. For the customer, the TAT is decisive, as longer TAT results in higher cost due to increased demand for more spare parts. For the MRO, additionally the WT is decisive as WT directly impacts their cost as the people involved are paid related to their WT.

4. STATE-OF-THE-ART REPAIR PROCESS OF AVIATION COMPOSITE STRUCTURES

4.1. Process description

On a top level, the repair process of a CFRP structure in a repair shop is shown in FIG 5. The process starts with the part arriving at the shop site. Mechanics view the part, collect delivered tags and delivery note and bring it to the office. According to the information on the delivery note, the capability of repairing this structure in the shop is being checked. This check depends on the certification of the shop for various aircraft/part types. They receive a purchase order (PO) from the customer which is the official document for conducting their inspection. After the capability is assured, the part is being inspected. More details on this process are shown in FIG 6. After the inspection is performed, for the quotation, the duration and cost for the repair of the damaged part is calculated and written down in the quotation document. This offer is sent to the customer who decides if the suggested repair with corresponding cost and duration should be conducted. As soon as the customer approves the repair, the actual repair is started. This process is highly individual. There may arise many questions between mechanics and tester. Often, during repair, further damages are found such that another inspection needs to be done and the repair order needs to be adjusted. Also, the revisions of the manuals need to be checked for updates regularly. After the structural repair is finished, the part is being transported to the painting hall with specific environmental requirements. The painted part is brought back to the repair shop and is finished by, e.g., rearming with pins and sealants. Afterwards, the final documentation is written according to the performed tasks. The certifying staff checks the documentation for completeness and prepares and signs the release document, e.g. the EASA Form 1 for the EASA or the FAA approval document. The repaired part is returned to the customer with the release document as well as other important documents. The defect parts have to be made unfit to fly and are then scrapped. The folder with all (printed) documents related to this repair is archived in a central archive.

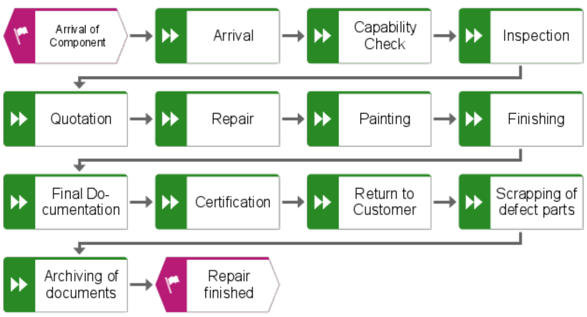


FIG 5. Process mapping: Top Level of CRFP repair process.

As explained in section 3.1.2, this top level process model is unsuitable for some purposes, e.g. for the mechanic to perform the tasks. Hence, the next level of detail is described for the inspection process (see FIG 6). First, the inspection order is written by the work preparation team. Then, the tasks written in the inspection order are performed and signed on the inspection order. Depending on the tasks to be performed, the part first needs to be mounted at a jig, then it has to be cleaned, the paint as well as plugs and panels are removed, some measurements are performed, the electric installation and paint are insepcted, a hidden damage inspection is performed and it is checked for foreign object damage (FOD). If applicable, nondestructive testing (NDT) is performed by a certified tester. All these functions marked with a gray background in FIG 6 can be summarized as *Perform tasks according to the inspection order*. At the end, the findings are written down in the inspection report.

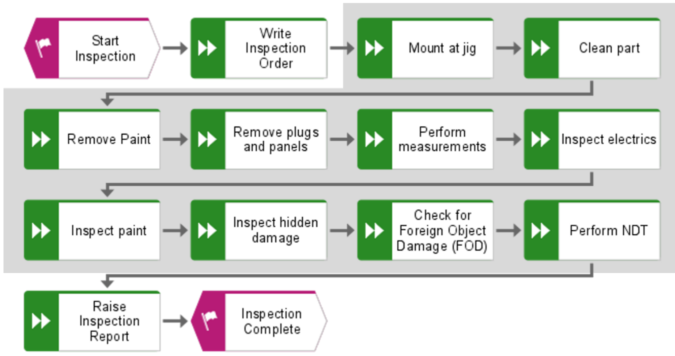


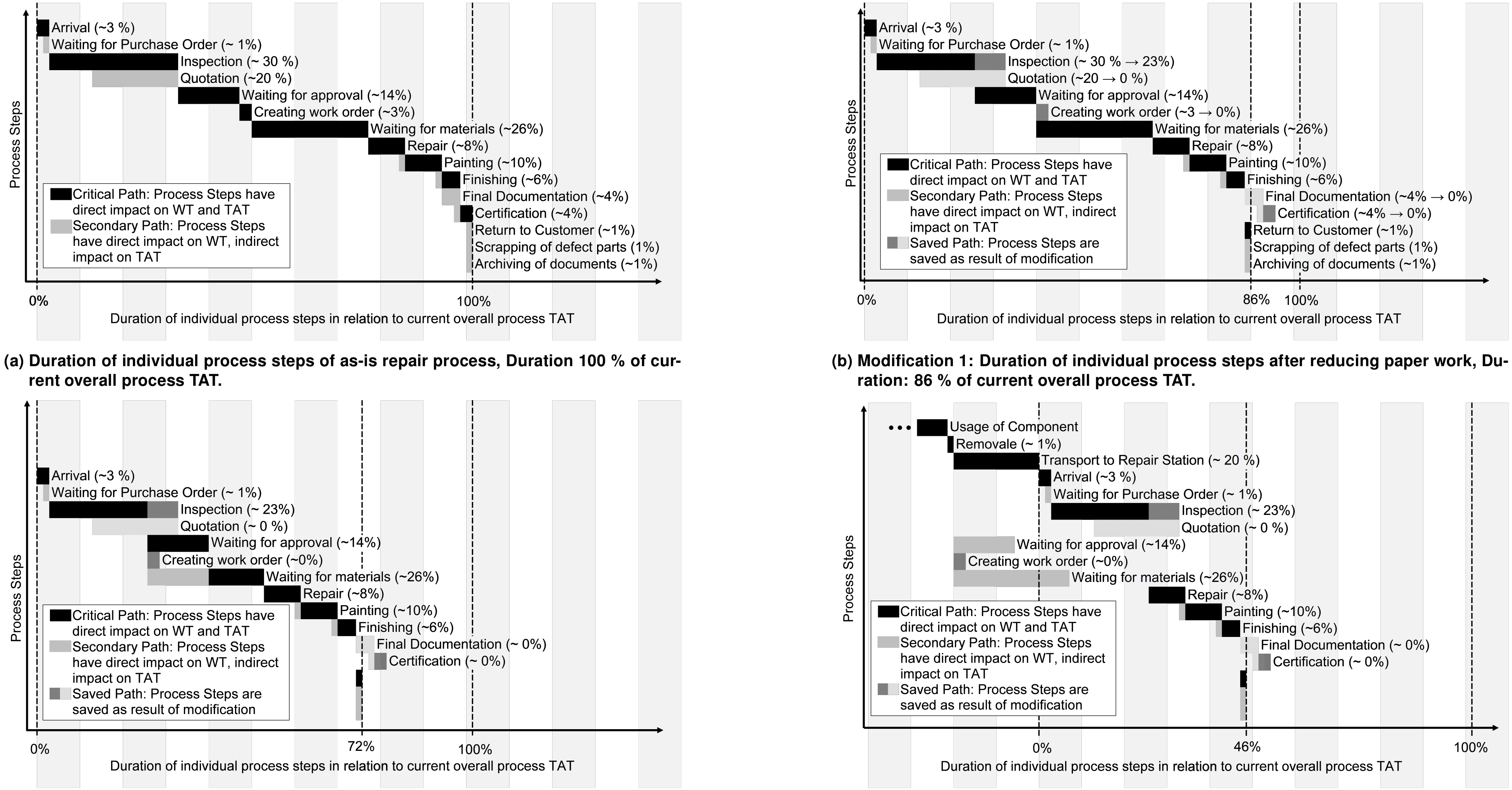
FIG 6. Process mapping: Detailed description of inspection process.

4.2. Process analysis and identification of potential modifications

The top level process as shown in FIG 5 is analyzed with respect to the TAT of the individual process steps. The sequence of processing times are graphically shown in FIG 7(a) with the relative durations of the individual steps in relation to the overall process duration, rounded to the nearest whole number. The relative durations of the individual steps sum up to more than 100%, as some of the subprocesses are executed in parallel, as shown in gray color in FIG 7. These tasks do not directly prolong the process TAT. However, they impact the WT and hence, result in higher process cost. During around 40% of the processing time, the repair shop has to wait for either approval by the customer or materials from suppliers. In FIG 8, the duration of the individual steps in the subordinate inspection process is shown.
During inspection, 55 % of the TAT are WT, hence actual work is performed. The paper work of 23% of the inspection TAT (30% of overall process), makes up 23% · 30% = 7% of the overall process TAT.

As both the waiting for externals as well as the paper work take a substantial amount of time, the process steps of the overall process as shown in FIG 5 are divided into the three groups *Waiting*, *Paper Work* and *Active On-Part Work* as following:

- The *Waiting* group consists of the three steps Waiting for Purchase Order, Waiting for approval, Waiting for materials, where the last two are on the critical path (shown in black in FIG 7) and add directly to the overall process TAT duration with 40 %.
- The second group, *Paper Work* is summarized as the process steps Quotation, Creating work order, Final Documentation, Certification and Archiving of Documents. On the critical path are Creating work order and a part of certification with 7% of the overall process TAT.



(a) Duration of individual process steps of as-is repair process, Duration 100 % of current overall process TAT.

(b) Modification 1: Duration of individual process steps after reducing paper work, Duration: 86 % of current overall process TAT.

(c) Additional Modification 2: Duration of individual process steps after optimizing internal process, Duration: 72 % of current overall process TAT.

(d) Additional Modification 3: Duration of individual process steps after optimizing external process, Duration: 46 % of current overall process TAT.

FIG 7. Repair process of CFRP structure: Duration of individual process steps of current process and potential of outlined modifications.

- The group of *Active On-Part Work* process steps consists of the steps Arrival, Inspection, Repair, Painting, Finishing, Return to Customer, Scrapping of defect parts. On the critical path are Arrival, Inspection, Repair and the majority of painting and finishing summing up around to 53 % of the overall process duration.

However, as can be seen in FIG 8, also for steps in the active On-Part group - here for the example of the inspection process - , a part of their processing time is still used for waiting or paper work tasks. Thus, the actual waiting times and paper work duration in this exemplary process are actually higher than the 40%, respectively 7%: As shown above, 23% of the inspection time are used for paper work which corresponds to additional 7% of the overall process duration, summing up to 14% paper work for the overall process TAT. For the other active-on part process steps, also part of the TAT is used for paperwork or waiting times. As however the exact times are not shown here, in the following, we use the above numbers. This amount of paper work and waiting time for externals reduces significantly the efficiency of the process. Possible modifications for a more efficient process are shown in the following TAB 1.

TAB 1. Possible modifications for reducing waiting times and time for paper work in process.

Bottleneck	Proportion of process duration	Possible modification
Waiting times for externals	40 %	· Better process planning of the internal process · Earlier order through data availability of previous external process
Paper work	14%	· Development of automated, digital documentation tools

4.3. Potential modifications for optimizing the process

As summarized in TAB 1, there are two approaches to shorten the process duration: By reducing waiting times for externals, up to 40% of time could potentially be saved, by optimizing the documentation, up to 14% of the overall duration could be saved. In the following, some ideas for realizing the modifications are outlined.

4.3.1. Reduce paper work via digital documentation

As can be seen in TAB 1, around 14% of the overall process TAT is used for documentation. This contributes directly to the WT. Hence, by reducing the duration for documentation, both the WT and the TAT can be reduced, resulting in lower cost for the MRO and the customer. By implementing automated documentation tools, the documentation could be generated directly when executing tasks, so that no additional time has to be used for paper work. The potential consequences for the TAT are shown in FIG 7(b), if the duration for paper work was reduced to zero. For paper work on the secondary path, the TAT is not reduced, however, the WT is impacted significantly. As in aviation, safety and reliability are ensured by documentation of the various processes, the documentation per se cannot be left out. However, it is possible to modify the process of documentation. At the moment, the work is documented in paper format. The documents are filled in in different ways, i.e. by different programs of different PCs or just hand-written notes. Thus, a lot of breaks in continuity arise and a lot of information needs to be copied from the source and pasted into another document. One possibility to overcome these breaks in continuity is to implement a digital solution for documentation. At the end of the process, a summary of the process, if needed in paper format, could still be generated in an automated way and then printed. In order to provide a digital documentation tool, first all relevant documents with related information need to be identified. For this identification as well as the implementation of digital documentation, further research needs to be conducted.

4.3.2. Reduce waiting times internally via better process planning

The waiting time for externals takes 40% of the overall process TAT (see TAB 1). This can be split up to 14% for approval by the customer and 26% for waiting for materials. If the repair shop could predict the decision for approval of the customer, the shop could already order the materials if an approval is predicted. The waiting time for approval will not be shortened as the customer will not change its time for the decision-making process. Neither will the waiting time for materials change as the logistics of the suppliers can not be changed by internal process modifications. However, if the repair shop predicts the approval of the customer, it can send the order for materials at the same time it sends the quote to the customer (see FIG 7(c)). Then, the waiting time for approval elapses in parallel to the waiting time for materials, which would result in a potential reduction of 14% of the initial process duration. One possibility to predict the decision of the customer for approval is to use a database for historical damages and the corresponding approvals. Relevant parameters as e.g. damage size and previous damages have to be captured. With the use of decisive algorithms, an estimation for the approval could be predicted based on historical data in the database. The identification of the relevant parameters as well as a suitable data management system and a suitable algorithm for decision making needs further research and will be investigated in future work.

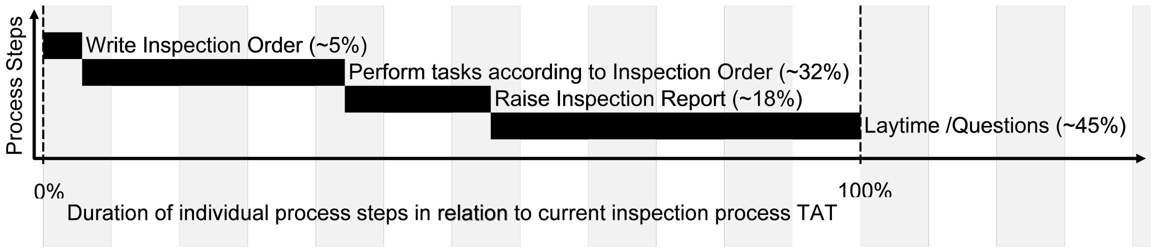


FIG 8. Duration of individual process steps of the inspection process.

4.3.3. Reduce waiting times externally via earlier data availability of previous external process

As the waiting times of 40% are waiting for externals, the duration for waiting cannot be easily shortened by modifying the internal MRO process in the repair shop. However, as shown in FIG 7, only the durations of process steps on the critical path (shown in black) add up directly to the overall process duration. Therefore, if one could shift the waiting times into the secondary path (shown in gray), or even before the actual MRO process, the waiting for externals does not contribute to the overall process TAT in the MRO shop. Indeed, before the component arrives at the repair shop, there is a pre-process of detecting the damage and transporting the part to the MRO shop (see FIG 9).

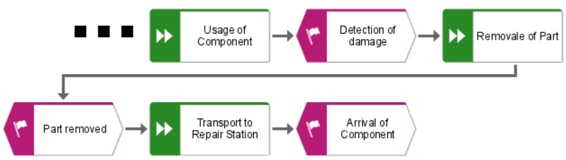


FIG 9. Process of part being processed before its arrival at the repair shop.

The transportation takes the same time as 20% of the overall repair process (shown in FIG 7(d)). Analogous to the previously mentioned database of historical damage information for decision support, a similar approach could be used to assess the damage at the removale location. Instead of transporting the component to the repair shop, inspect it there and then predict the approval by the customer based on a database, a more sophisticated damage assessment could already take place at the removale location. In a database, historical damage information could be stored and a suitable algorithm could predict the repairs, the corresponding economic parameters and therefore also the approval decision of the customer. Hence, if an approval by the customer is predicted, the quote to the customer as well as the order for material could be sent at the time when the component starts its transport to the repair shop. Then, a preliminary approval by the customer is available before the component arrives at the station and the material arrives during the inspection process of the repair shop (see FIG 7(d)). Hence, both the waiting for approval as well as the waiting for materials are on the secondary process path and do not add up to the overall process TAT. This leads to a further reduction of the overall process TAT by 26% (see FIG 7(d)). The prerequisites for such a described estimation tool based on database and prediction algorithm as well as the implementation and detailed benefits for the overall maintenance processes are to be identified in further research.

4.4. Summary

At the moment, the repair process of composite structures in a dedicated repair shop is characterized by manual task execution, focus on the individual process steps without interaction between them and documentation in paper format. The general sequence of process steps (see e.g. FIG 1) should not be changed, as it is the logical order to inspect the part after the damage is detected, then assess the results and define the repair, then execute it and document the work. However, there are some bottlenecks in the execution of these steps (see TAB 1), reducing the efficiency of the repair shop: With a automated documentation tool, the duration for documentation (around 14%) could be saved, resulting in a reduction of the overall process TAT to 86% (see FIG 7(b)) as well as a reduced WT, hence reduced cost for the MRO shop. With the use of a database of historical data to predict the approval of the customer, material could be ordered earlier, hence the waiting time for material could elapse parallel to the waiting time for the approval, which further reduces the process TAT by 14%, to a duration of 72% of the current process TAT (see FIG 7(c)). A third approach would be the usage of a sophisticated database and a corresponding decision algorithm to predict the approval of the customer already at the removale location. Then, the material could be ordered while the component is transported from the removale location to the repair station. Hence, the waiting for approval as well as the waiting for material elapse on the secondary path, resulting in a further process TAT reduction by 26 %, to a duration of 46% of the current process TAT (see FIG 7(d)). All these approaches would result in a more time-efficient repair process. The detailed prerequisites as well as their implementation need to be further investigated in future research.

5. CONCLUSION AND OUTLOOK

The degree of digitalization in the aviation maintenance sector is behind the state-of-the-art degree in other industries. Possible explanations are the individual processes with few occurences, the conflicting interests of the involved stakeholders as well as a variety of non-standardized data formats. Approaches for digital support systems and process modeling approaches reach form e-maintenance, ontology- or blockchain-based technologies to digital twins. By overcoming this lack of digitalization, the efficiency of the repair process of composite structures could be increased, as the waiting time for externals as well as the documentation work could be significantly reduced resulting in a shortened overall process duration. Further research should be conducted on a quantification of the process analysis including cost and ecological impacts of the individual process steps and possible modifications. The details for the described modification approaches including the prerequisites, the identification of relevant parameters, the choice of suited technologies, databases and algorithms as well as their implementation are also to be investigated in further studies.

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References

[1] Global fleet and MRO market forecast 2023 - 2033. Standard, 2023.

[2] R. Schmücker, H. Meyer, R. Roedler, F. Raddatz, and R. Rodeck. Digitalization and data management in aircraft maintenance based on the example of the composite repair process.

[3] P. Depaoli, S. Za, and E. Scornavacca. A model for digital development of smes: an interaction-based approach. *Journal of Small Business and Enterprise Development*, 27(7):1049–1068, 2020.

[4] M. C. Herkes and G. Oversluizen. Using a systems approach to model a process digital twin. pages 1906–1911, 2022.

[5] J. Friederich, G. Lugaresi, S. Lazarova-Molnar, and A. Matta. Process mining for dynamic modeling of smart manufacturing systems: Data requirements. pages 546–551, 2022.

[6] Mark Dodgson, David M. Gann, and Nelson Phillips. *The Oxford Handbook of Innovation Management*. Oxford University Press, 2013.

[7] M. Eigner and M. T. Zavareh. *Digitalization of the Engineering Supported by System Lifecycle Management (SysLM)*, volume 640 IFIP of *IFIP Advances in Information and Communication Technology*. 2022.

[8] T. G. Kormin, V. A. Ovchinnikova, and J.-D.B. Tsumbu, editors. *Simulation modeling of manufacturing*, volume 1047, 2021.

[9] D. Krenczyk, editor. *Dynamic simulation models as digital twins of logistics systems driven by data from multiple sources*, volume 2198, 2022.

[10] Yonghuai Zhu, Jiangfeng Cheng, Zhifeng Liu, Qiang Cheng, Xiaofu Zou, Hui Xu, Yong Wang, and Fei Tao. *Production logistics digital twins: Research profiling, application, challenges and opportunities*, volume 84. 2023.

[11] M. P. Sadar, K. G. Rajmore, M. K. Rodge, and K. Kumar. Digital manufacturing approach for process simulation and layout optimization. *Materials Today: Proceedings*, 74:642–649, 2023.

[12] F. Seixas-Lopes, J. Ferreira, C. Agostinho, and R. Jardim-Goncalves. *Production Process Modelling Architecture to Support Improved Cyber-Physical Production Systems*, volume 577 of *IFIP Advances in Information and Communication Technology*. 2020.

[13] A. Szajna, R. Stryjski, W. Wozniak, N. Chamier-Gliszczynski, and T. Królikowski. The management of digital data using innovative technologies. pages 3143–3152, 2022.

[14] M. Vjestica, V. Dimitrieski, M. Pisaric, S. Kordic, S. Ristic, and I. Lukovic. Towards a formal description and automatic execution of production processes. pages 463–468, 2019.

[15] L. Merkle, L. Moers, and M. Lienkamp, editors. *Stakeholder Analysis of Digital Twins for Battery Systems*, 2020.

[16] Bishal Raj Karki and Jari Porras. Digitalization for sustainable maintenance services: A systematic literature review. *Digital Business*, 1(2):100011, 2021. ISSN: 26669544.

[17] H. Koornneef, W.J.C. Verhagen, and R. Curran. A decision support framework and prototype for aircraft dispatch assessment. *Decision Support Systems*, 135, 2020.

[18] H. Koornneef, W.J.C. Verhagen, and R. Curran. A web-based decision support system for aircraft dispatch and maintenance. *Aerospace*, 8(6), 2021.

[19] Peter Korba, Patrik Šváb, Michal Vereš, and Ján Lukáč. Optimizing aviation maintenance through algorithmic approach of real-life data. *Applied Sciences*, 13(6):3824, 2023.

[20] Alexandre Muller, Adolfo Crespo Marquez, and Benoît Iung. *On the concept of e-maintenance: Review and current research*, volume 93. 2008.

[21] R. KARIM O. CANDELL and A. PARIDA. Development of information system for e-maintenance solutions within the aerospace industry. *International Journal of Performability Engineering*, 7(6):583, 2011.

[22] A. Apostolidis, M. Pelt, and K. P. Stamoulis, editors. *Aviation data analytics in MRO operations: Prospects and pitfalls*, volume 2020-January, 2020.

[23] A. A. Abdallah and I.-S. Fan. Towards building ontology-based applications for integrating heterogeneous aircraft maintenance records. pages 293–299, 2022.

[24] W.J.C. Verhagen and R. Curran. An ontology-based approach for aircraft maintenance task support. pages 494–506, 2013.

[25] P. Luis, L. Gaëlle, M. Yue, and R. Chantal, editors. *Knowledge discovery for avionics maintenance support*, volume 2018-September, 2018.

[26] Clemens Gróf and Alexander Kamtsiuris. *Ontology-based Process Reengineering To Support Digitalization Of MRO Operations: Application To An Aviation Industry Case*, volume 104. 2021.

[27] G.T.S. Ho, Y. M. Tang, K. Y. Tsang, V. Tang, and K. Y. Chau. A blockchain-based system to enhance aircraft parts traceability and trackability for inventory management. *Expert Systems with Applications*, 179, 2021.

[28] L. Li, S. Aslam, A. Wileman, and S. Perinpanayagam. Digital twin in aerospace industry: A gentle introduction. *IEEE Access*, 10:9543–9562, 2022.

[29] M. Xiong and H. Wang. Digital twin applications in aviation industry: A review. *International Journal of Advanced Manufacturing Technology*, 121(9-10):5677–5692, 2022.

[30] F. Zhao, X. Zhou, and L. Dong. An intelligent digital-twin-based strategy for the inspection and repair of aircraft skin cracks. *Guti Lixue Xuebao/Acta Mechanica Solida Sinica*, 42(3):277–286, 2021.

[31] C. Kellenbrink, N. Nübel, A. Schnabel, P. Gilge, J. R. Seume, B. Denkena, and S. Helber. A regeneration process chain with an integrated decision support system for individual regeneration processes based on a virtual twin. *International Journal of Production Research*, 60(13):4137–4158, 2022.

[32] Heinrich Seidlmeier. *Prozessmodellierung mit ARIS®*. Springer Fachmedien Wiesbaden, Wiesbaden, 2019.

[33] Jan Mendling. *EPCs*. Springer, Berlin, Heidelberg.