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ORIGINAL PAPER

Digital twins in aircraft production and MRO: challenges and opportunities

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Abstract

The digital twin (DT) concept, value-adding connecting the real and digital world, has been a rising trend in recent years, while the implementation and observation of challenges are still subject to research. Implementations of holistic Digital Twins of tangible and intangible assets of complex products or processes are often ideal-theoretic; instead, only subsystems and processes are replicated, which digital representations serve specific, meaningful applications. Specifically, with its distinct characteristics, the aviation industry and its production show various future application scenarios, which we use case-driven outline in this work. Therefore, we first summarize common, industry-neutral challenges of implementing Digital Twins and give an overview of aircraft production characteristics. Then, we will outline different fields of utilizing the Digital Twin concept and highlight integrational, organizational, and compliance-related challenges as well as opportunities in the context of aircraft production and Maintenance, Repair, and Overhaul (MRO). The use cases are located at different aircraft life cycle phases, from production system development, production supplying logistics, and Quality Assurance (QA) up to retrofit.

Keywords Digital twin · Aircraft · Production · MRO · Challenges · Opportunities · Manufacturing · Assembly · Quality assurance · Product lifecycle management

1 Introduction

Implementing a holistic Digital Twin (DT) as an aircraft's virtual replica is challenging for various reasons, ranging from the asset's extended lifespan over system complexity and customer-individual configurations to the number of involved stakeholders throughout its life. In the Begin-of-Life (BoL), stakeholders are mainly the aircraft manufacturer and Original Equipment Manufacturer (OEM) of individual (sub-)systems like the engine or cabin as well as lower tier suppliers. In the BoL stage, sub-contractors may be involved in production[1] steps, usually in component manufacturing and structural assembly. Later, several service providers and stakeholders from the previous lifecycle phase share the life-extension market, including the maintenance provider, as well as retrofit and remanufacturing services in the Mid-of-Life (MoL). Therefore, the aircraft is a complex system of many subsystems designed, manufactured, operated, and serviced by various actors.

Facing severe regulation from air authorities, e.g., European Union Aviation Safety Agency (EASA), stakeholders act in a narrow set of rules in all of their activities. As a result, theoretically, the data basis for an aircraft's consistent Product Lifecycle Management (PLM) and Manufacturing Process Management (MPM) exist. However, it lacks interconnection of data and information, consistent model-based management, and collaborative cooperation across stakeholders and beyond lifecycle phases. Current reasons mainly include intellectual property boundaries and the absence of timely, time-bound economic added value perspectives.

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1 We use the terms "production" and "manufacturing" as per the German language distinction. Manufacturing is technology-centric and encompasses processes that convert raw materials into tangible goods. In contrast, production is the overarching term encompassing all processes involved in creating consumable goods or capital assets, spanning, e.g., manufacturing, assembly, logistics, and financial activities.

However, there are various opportunities to implement DTs of an aircraft's (sub-)systems and production processes to increase productivity and subsequently reduce costs.

Based on use cases, such as flexible cabin assembly, production-supplying logistics, assisted Quality Assurance (QA), and retrofit processes, that originate from current and past research projects in collaboration with companies in the aviation industry, we will elaborate on prospects and especially the challenges of implementing and utilizing DTs over the aircraft's lifecycle.

Developing, deploying, and organizational integrating a DT encounter, on the one hand, general challenges that multiple industries face, e.g., technical standards and, at best, open software that implement these, but also domain-specific formidable obstacles more concerning the individual products, processes, or resources and their intrinsic characteristics targeting the organization and regularities.

In recent years, different standardization efforts have led to projects and groups like Gaia-X[2], including Catena-X[3], or the Industrial Digital Twin Association (IDTA)[4] that target digitalization challenges including the concept of the DT. Gaia-X is a European initiative to build up a federated secure industrial data infrastructure; Catena-X is an automotive industry-driven project targeting developing an open, standardized data ecosystem for the complete automotive supply chain. The IDTA is a cross-domain initiative promoting the DT concepts through standardization efforts to increase interoperability especially. The IDTA introduced the Asset Administration Shell (AAS) and submodels that describe an asset's content-related or functional aspects. Catena-X and the IDTA work on unified data models / semantics and provide the corresponding open software (libraries). So, these initiatives focus on particularly the technical side also in the context of compliance-related challenges, such as data ownership.

This use case-driven work does not dive deep into the actual implementation of a specific DT on a technical level — we highlight further literature when possible — rather than bringing up novel use cases in the aircraft production and MRO domain on a conceptual level. The work can be understood as a forward-looking exercise based on our gathered previous knowledge during research and development in the outlined domain.

The rest of this work is structured as follows: first, the common DT definition, as well as challenges, will be presented (Sect. 2), and discrete production steps in an aircraft's lifecycle will be described (Sect. 3). In Sect. 4, aviation industry-specific challenges and opportunities in deploying DTs in the different lifecycle phases will be discussed. Finally, the results will be summarized (Sects. 5 and 6).

2 The Digital Twin (DT) concept

Conceptually introduced in the early 2000s by Michael Grieves in the context of Product Lifecycle Management (PLM) as Mirrored Space Models [4], more widely established with a NASA publication from Edward Glaessgen and David Stargel [5], the DT concept has evolved from the digital replica of a product within the context of PLM to a variety of tangible and intangible assets in different domains.

After the term "Digital Twin" was more widely established, multiple authors aligned with the sub-classifications of Digital Model, Digital Shadow, and Digital Twin targeting the level of integration [6–8]. In a Digital Model, the bi-directional data flow between the physical instance and the digital object is manual, while in the case of the Digital Shadow, the data flow to the digital object is automatic. The next integration step is then the bi-directional automatic data flow from and to the digital object [9]. This sub-classification focusing only on the type of data flow and linking this to the terms Digital Model and Digital Shadow are meanwhile extended and refined to classify digital representations of physical assets, which otherwise would not fall under this taxonomy.

In this work, we follow the definitions of the *International Academy for Production Engineering* (CIRP), which defines the DT as a "digital representation of an active unique product or product-service system that comprises its selected characteristics, properties, conditions, and behaviors by means of models, information, and data [1]." The product is either tangible, e.g., a real device or machine, or an intangible asset, e.g., a process. The core elements of each twin are the Digital Master (DM), the Digital Shadow (DS), and a value-adding, meaningful linkage enabling an application (Fig. 1).

The DM is the instance-unspecific template containing the application purpose-specific models of the asset's (sub-)systems. It is typically a composition of multiple domain-specific models linked together to model the physical asset's respective (sub-)systems and enable the value-adding applications. Models from a virtual or digital prototype — a virtual prototype has no physical counterpart — can be reused in the final DM.

All instance-specific data are contained in the DS, forming the data sink for the data that flows from the physical instance to the digital representation. While the DM is copied during the instantiation of the DT in the phase of the physical instance's manufacturing, the DT becomes only a unique reflection given the DS.

[2] https://gaia-x.eu.

[3] https://catena-x.net.

[4] https://industrialdigitaltwin.org.

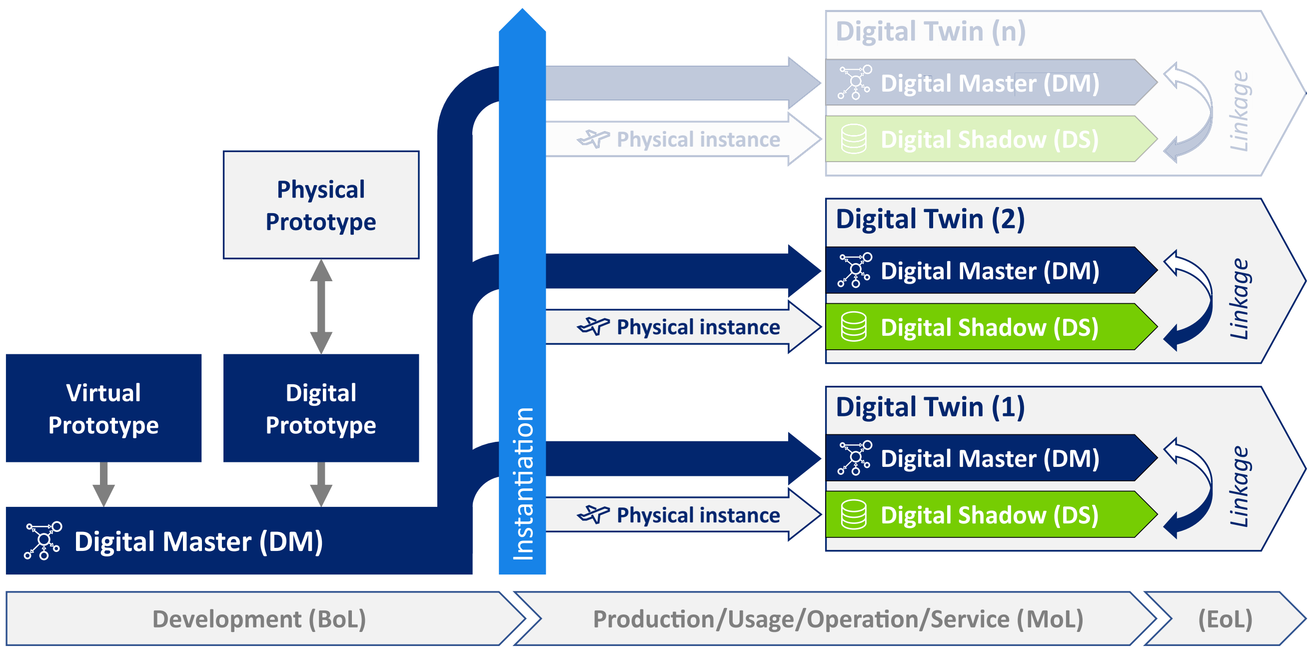

Fig. 1 The generic Digital Twin (DT) concept (based on [1–3])

The linkage of the DM and DS combines to a DT by, e.g., algorithms or simulations, usually enabling applications like monitoring or prediction [10]. The DT is the pinnacle of digitalization, allowing data and information to flow between an asset's digital and real replica, increasing its added value.

With the given definition from the CIRP, we can classify the parts of a digital representation in various use cases while not only focusing on the data flow from and to the digital and physical world. Moreover, [1] defines an 8-dimensional model characterizing the different levels of maturities of a DT. The focus on the manual/automatic data flow, as in [9], now becomes the "connectivity mode" dimension in this 8-dimensional model. Further dimensions are the integration breadth, update frequency, Cyber-Physical System (CPS) intelligence, simulation capabilities, digital model richness, human interaction, and scope in the product lifecycle.

2.1 Applications and integration breadths

The more generic classification of the DT's components and the definition of the term itself focus on tangible and intangible assets. So, not only a physical product can be digitally replicated but also processes and a composition, e.g., a product-service system. To further clarify the twin's scope and / or its integration breadth during this work, we propose a taxonomy spanning over the tangible/intangible dimension as depicted in Fig. 2.

Digital replicating a tangible asset as a whole system or only particular subsystems, e.g., an engine or only a particular engine blade, will we term in this work Digital "*Product*" Twin. Here, the digital counterpart may incorporate CAD data, checklists, or the respective regularities. Thus, the DT that primarily focuses on the tangible product will fall under this category even in the case that partly product-related processes are mapped as long as the tangible asset is in the center of the twin's integration breadth.

On the other hand, the DTs of the operating resources of the production or MRO processes that include, e.g., robots, assistance systems, or (intelligent) tools, will be summarized as Digital "*Operating Resource*" Twin.

Moving further to the intangible side, as depicted in Fig. 2, the Digital "*Production Process*" Twin and Digital "*MRO Process*" Twin primarily focus on process parts of the Product–Process–Resource (PPR) model [11]. Typical production processes that are digitally replicated are, e.g., assembly, machining, or QA processes. In contrast to the tangible side, where we do not distinguish between MRO and production, we do so for the intangible side, with production as the creation of a (sub-)system in its BoL and the MRO activities, basically since they obey different kind of characteristics as we will describe in more detail in Sect. 3. Typical MRO processes are, e.g., scheduled and unscheduled inspections of parts or overhauling cabin components.

Since individual twins of only products, processes, or resources usually do not sufficiently serve an application, combining the previously named twins focusing on either the intangible or tangible side is subject to industrial practice, development, and research. We, therefore, introduce the Digital "*(Sub-)System / (Sub-)Process*" Twin — the combination

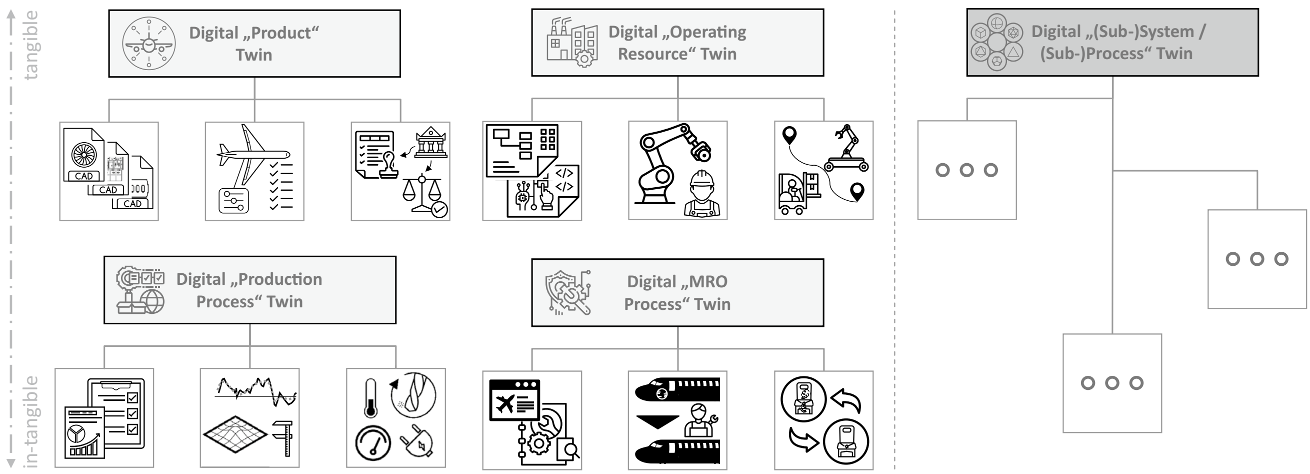

Fig. 2 The different Digital Twin (DT)s of (sub-)systems and (sub-)processes within the aircraft production and MRO, which we focus on in this work

of the intangible and tangible side. However, our main claim is that a twin is primarily built up, focusing on one of the sides, as we highlighted in our taxonomy. This differentiation is also subject to state-of-the-art software systems in the product development and production context. Product Data Management (PDM) software focuses on the product, e.g., through CAD data, but also allows for representing Product Manufacturing Information (PMI) or manufacturing instructions. On the other hand, a typical Manufacturing Execution System (MES) focuses primarily on the monitoring, tracking, documentation, and control of the production process. Obviously, one can import and make use of the product's CAD data, but the original intention of the software is to represent the process, including, e.g., digitally, data/information models that may form the DM.

In conclusion, in the context of refining what kind of twin we speak during our use case study, the proposed taxonomy helps differentiate between the PPR elements. However, linking or exchanging information between the individual twins and widening the integrational breadth is still allowed. Therefore, the boundaries of these twins are to be regarded as fluid rather than strictly separated.

2.2 Challenges

As already motivated in the introduction of this work, the design, implementation, deployment, and organizational integration of DTs face several challenges. On the one hand, there exist product/process-dependent ones; on the other hand, commercial or business barriers often result in engineering or technical-independent challenges.

Product/process-dependent

Engineering or technological challenges mainly address information and data issues similarly found in PDM, which are still subject to development and research since long before the introduction of the DT concept. Management and organization are key enablers besides the data and information quality. Simply put, "product data does not look after itself" [12].

In high-value manufacturing and on the data and information management side, [13] underlines especially system complexity and missing standards as issues that inhibit the effective deployment of DTs in the industry. On the other hand, since twins are information systems serving an information demand, inputs, and outputs are presumably afflicted by issues commonly measured in data or information quality criteria, including, e.g., contextual or representational issues [14].

Commercial/business-dependent

Mostly independent of the product/process, businesses face organizational challenges that influence the implementation and deployment of DTs. In this context, [13] highlights scalability, data/information sharing, sector servitization, and digital security. Interoperability inside a team is of different complexity than in the company or even across stakeholders. So, e.g., scaling a DT from a specific application on one shopfloor to an integrated information system across multiple manufacturing sites is subject to technical and organizational restrictions closely related to data/information sharing and ownership hurdles. Regarding high-value products, profits increase with product–service systems or twins after the product leaves the manufacturer. Here, [13] outlines that providing the service in the usage life phase is currently more challenging than manufacturing the product since companies often struggle with digital transformations.

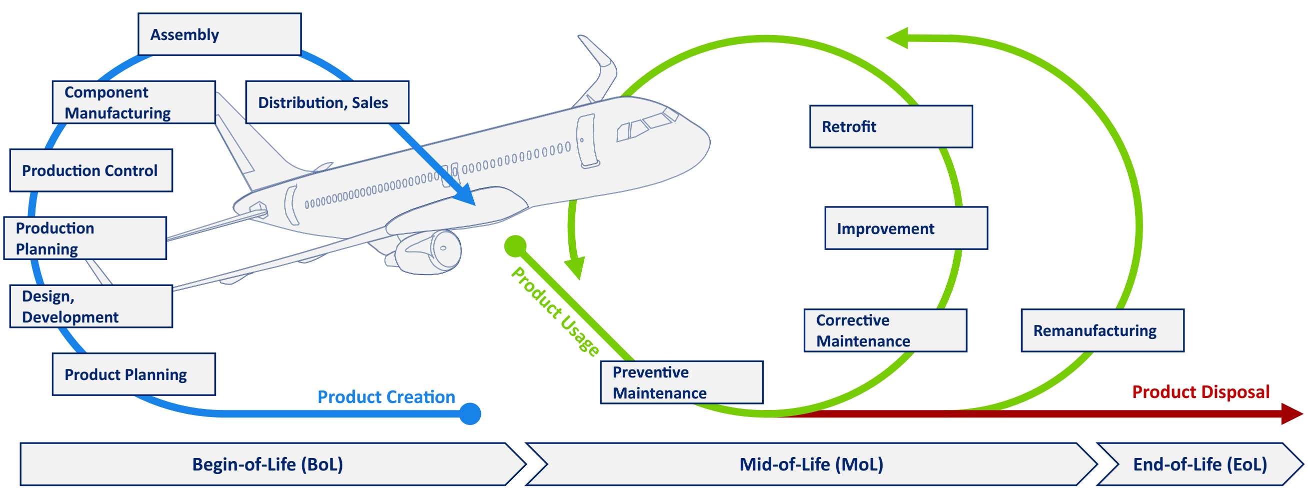

Fig. 3 An aircraft's lifecycle from product creation to product disposal (based on [16, 17])

Recently, [15] presented an empirical study on implementing DTs based on interviews with experts from the industry comprising the most challenging issues, basically summarizing the previously mentioned ones in three different categories:

1. **Integrational challenges**
   - Missing standardized structure & semantic
   - Complexity of integration
   - Interfaces
2. **Organizational challenges**
   - Qualified staff
   - Collaboration
   - Value for management
3. **Compliance-related challenges**
   - Data protection/ownership

In Sects. 4 and 5, we will use this taxonomy to categorize the aviation production and MRO industry-specific DT challenges systematically.

3 Production and MRO in the aircraft lifecycle

As a large and complex capital asset, developed and manufactured at great expense, the aim is always to keep an aircraft's profitability by ensuring airworthiness at all times. The typical lifespan of a passenger aircraft can exceed 25 years, while freighter aircraft usually last longer [18]. Accordingly, an aircraft's product lifecycle is characterized by numerous repetitive development and production cycles, as shown in Fig. 3. The following subsections will outline and conclude the characteristics of production processes in the aircraft's lifecycle.

3.1 Begin-of-life (BoL)

Planning the production must be an integral part of the development and design of the aircraft or Head-of-Version (HoV). In practice, product and production system development tend to be sequential, resulting in multiple iteration loops and a lengthy production ramp-up [19]. For example, if an airline orders a new, individualized HoV, production planning is started after all product-specific details and changes have been negotiated. That applies not only to the aircraft manufacturer itself but also to its numerous international suppliers providing their individual made-to-order components by a fixed deadline. However, production methods, operating resources, materials, personnel requirements, and times must be defined before production or external procurement of sub-components can be commissioned, again shifting the production-ready state [20].

Numerous subassemblies of the aircraft's fuselage, engines, avionics, and interior are pre-assembled externally and integrated into the HoV at a specified time in the final assembly line, which is rather a site than a line assembly due to the size of the structures [21, 22]. All production and assembly processes depend on production planning, high-performance production control, and highly available external and internal production-supplying logistics processes. Due to the criticality of safety in aviation, high approval restrictions exist, and all processes are qualified and monitored by OEMs, customers, or authorities, again increasing the list of the stakeholders in aircraft production [22].

3.2 Mid-of-life (MoL)

After appropriate tests and final acceptance, the aircraft usage phase starts with its maintenance and retrofit activities by the aircraft operators and MRO contractors. Mandatory checks or preventive maintenance intervals are prescribed for every subsystem installed in the aircraft to prevent critical failures and accidents [23]. MRO processes range from a simple visual on-site inspection, such as on-wing engine boroscopy [24], to the complete removal, testing, and overhaul of entire systems, such as crack detection and repair of engine combustion chambers [25]. So, after preventive, the corrective activity follows. Besides, during regular maintenance intervals or in the event of acute safety-relevant updates, maintenance organizations must introduce updates to hardware and software as specified, e.g., in Service Bulletins or Airworthiness Directives issued by approved design organizations or a regulatory body [26].

In the MoL, special importance is attached to so-called retrofit and remanufacturing processes distinguished by either ameliorating through innovations and new functions or rebuilding a component to its original specification to prevent complete disposal, respectively. Remanufacturing is usually utilized on high-value components like the engine blades [22], while retrofit modernizes, e.g., the cabin [27]. Due to the aircraft's high-value character, all previously mentioned activities are time-critical while also requiring accurate, compliant documentation. Therefore, activities like job preparation, logistics, and quality assurance involve even more complexity than during the BoL due to the increased time factor.

3.3 End-of-life (EoL)

Once the airframe finally reaches its EoL, the wear-out stock of only a few subsystems and components is usually consumed while others are still open for life-extension strategies. For example, cabin elements, engines, or avionics systems are often removed, refurbished, or reused in another aircraft [28]. Disassembly, repair, and assembly processes are then again subject to aircraft production activities.

3.4 Peculiarities of production and MRO activities in aviation

To conclude from the previous overview of the different aircraft lifecycle phases and its corresponding activities, we summarize the particular characteristics of aircraft production and MRO as follows:

1. Due to a high degree of customization required for customer-specific configurations and low ordering volumes per customer, low production volumes (lot size 1) result, for which conventional automation approaches are too complex, expensive, and mostly infeasible;
2. Regulatory requirements necessitate a dependence on expert knowledge, such as for defect classification. That, alongside aspect (1.), results in mainly manual processes;
3. Efforts are made to maintain, remanufacture, reuse, and retrofit systems, subsystems, and components of aircraft due to their high value and long lifecycles;
4. The large structures and multiple hierarchy levels of assembly necessitate on-site final assembly;
5. Processes have evolved over time to meet both political requirements and the needs of globally dispersed stakeholders;
6. Due to a large number of suppliers providing modules, (sub-)systems, and components for the complex product system aircraft as well as a locally unbound and moving product, the production and MRO activities are mostly (globally) distributed;
7. Aviation authority regulations and the criticality of aviation safety require high levels of inspection, testing, occupational health and safety measures, certification, and documentation.

Concluding these points, the aviation industry stands apart from other industrial branches like automotive due to those unique domain-specific challenges. While these challenges may be demanding, they also present opportunities for innovation in the realm of DTs. In the following, we will elaborate on various use cases and reflect them on the above-outlined characteristics and requirements.

4 Use cases

The following use cases outline different options for deploying DTs from current as well as past related and the author's research. We structured the different views on a digital replica of a product, process, or resource by first stating the context, following different challenges that inhibit the DT creation, and eventually proposing the specific twin applications and opportunities.

4.1 Enabling co-development and co-customization in product and production system development

External drivers such as the coronavirus pandemic, raw materials and supplier parts shortages, emerging trends, and new technologies require flexibility and adaptability along the whole value chain. Increasing competition, cost

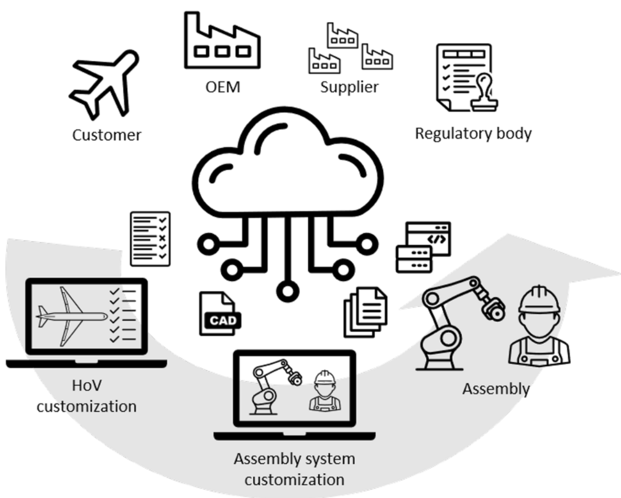

Fig. 4 Enabling seamless product and assembly system customization

pressure, and a focus on sustainability further challenge the aviation industry. Especially in the aircraft cabin, passengers and airlines demand customization of designs, layouts, and functionality as well as the integration of new digital technologies and services such as mobile phone connectivity to enhance customer experience and airline revenue. Therefore, the product, production, and assembly systems need to be flexible and modular; thus, product development and production planning are under pressure to cope with these changes in a timely and efficient manner [20] (Fig. 4).

Integrational and organizational challenges

Product development, production planning, and production lack connection and common data sinks to date. Some of the shortcomings are complicated, document-based workflows in development and change management, different software tools, data formats, and means of communication between stakeholders and different departments. As many subassemblies and parts are made-to-order in contracted manufacturing, harmonizing design decisions, production capabilities, and availabilities between integrator and supplier are especially challenging [20]. Here, considerations of intellectual property and core competencies of the companies additionally prevent full and efficient data exchange of, e.g., CAD models, drawings, work instructions, CAM data, and inspection reports [20].

Due to the high variance and mostly considerable age of underlying designs and processes, most development, customization, and planning activities are conducted manually by experts. Therefore, in combination with the problem of outdated or a lack of data, those activities take considerable time, might be unnecessarily repeated in other departments, and results can be sub-optimal or faulty [29]. Typically, these errors are discovered only at later stages, resulting in high costs for re-engineering and re-work [19].

The Digital Prototype (DP)

A solution here is co-development and co-customization in product development and production planning based on a Digital Prototype (DP) - a tentative digital model ready for later instantiation with data from the physical product or process to form a DT (s. Figure 1 for details regarding the DP). Therefore, a supportive customization toolchain, a common system understanding, and a single data source must be derived. New, model-driven instead of document-centric approaches are sought to offer these possibilities [30].

With the goal of a central, multi-level model as a DP, all relevant product information is modeled in this single source of truth. However, different views on information and communication with other necessary data models and software such as CAD, FE, or process simulation must be possible for different actors such as requirement, structural and electrical engineers, sales, and airline representatives.

The DP that arises during the co-development and co-customization can transform into the Digital Product and Production Process Twin after the instantiation of the tangible assets. These, in addition, can later be linked with further stages of the lifecycle, e.g., manufacturing and assembly planning, where the product architecture and functionality are required on a high abstraction level. Especially in assembly planning, model-based and automated approaches are currently of high research interest due to the high cost factor. The efficient adaption of assembly sequences, resource allocation, physical configuration, and automated implementation of changes in the corresponding work instructions, control systems, and software depend on structured and machine-readable models of the product and the assembly system-related data [31].

Higher level data and information generated in assembly planning through detailed steps like robot programming and simulation, feasibility, assembly time, and costs can be stored in the DP. Once enriched by real-world data, the DP turns into a DT, allowing analyses for the further improvement of product design and production planning itself but also reuse in a later life phase.

4.2 Shopfloor data acquisition for on-line process optimization

Aircraft design today is a digitalized and model-centric process. Complete digital models from the design phase allow the next phase of work preparation to efficiently apply simulative approaches: Enabling, e.g., optimization and selection of optimal production processes with low lead times and incorporating the latest manufacturing technologies right before production line design [32]. Thus — in

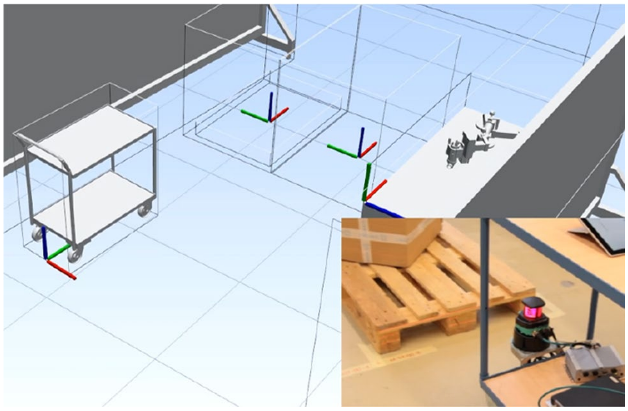

Fig. 5 A live representation of assets and their positions on the shopfloor

theory — resulting in an overall better manufacturing process, the more complete the design model is, as more optimization parameters and more impact factors can be considered in a reasonable amount of time over manual optimization and selection. In contrast to design and work preparation, all subsequent stages of the production process are characterized by a near-complete lack of digitalized or even digitized processes. This applies to the production process itself, as a primarily manual process, as well as associated logistics (Sect. 4.5) and quality control (QC) (Sect. 4.4) (Fig. 5).

Information-flow in production

The production of goods integrates vertically with the design and work preparation to the top and QC to the bottom. Horizontally, it integrates with the necessary logistics processes. Information flow from design and work preparation to production is mostly static: The product, processes, and tools are defined. The production stage and later QC may provide feedback on these prior stages. The scheduled production of parts, in turn, creates a demand for logistics to deliver the correct parts and materials per work step. Production communicates this demand to logistics. Logistics, in turn, may report information on availability and delivery/lead times.

As found by the authors of [33], large aircraft manufacturers' complex, multi-tiered supply chain structure is an inhibiting factor to implementing digitalization technologies. This supply chain structure also poses a problem for feedback from production to the design [34], as well as from logistics to production, as stakeholders for reception or retrieval of information cannot be identified easily.

Shopfloor digitalization

We envision a digitalized shopfloor and (multiple) twin(s) to consist of and support three key elements:

1. The digital thread of the manufactured product,
2. A process model,
3. A live representation of the process parameters and the environment.

The element (1) can be part of a Digital Product Twin while the elements (2) and (3) can be replicated in a Digital Production Process and / or Digital Operating Resource Twin. Especially, data and models from (1) can further be reused in the MoL again.

Building a live representation of the shopfloor (3) by acquiring the state (e.g., location or operating parameters) of materials, parts, and tools (Fig. 5) enables a rich understanding of the production state, its influences, and a product's history. Characterized by primarily manual production, assembly, and logistic processes, leveraging digital process models (2) and feeding a Digital Product Twin (1) is non-trivial in the aircraft industry. To support these, a precise and complete model of the environment requires the integration of multiple sensor modalities (optical, ultra-wideband, etc.) to generate data adhering to a common model language and the ability to integrate heterogeneous data (images, point clouds, pose information, etc.) and link these with data from the business domain, as proposed in [35].

These data can, in turn, be used to infer the state of and locally optimize and guide a manual process and its logistics by applying (2) and populating (1) to be used in QC and fed back to prior production stages.

Scheduling and feedback

Following, we briefly describe a selection of concrete use cases highlighting the benefits of a digitalized shopfloor and its process and product data. The authors of [36, 37] successfully maximize resource utilization in case of missing goods. By combining a process model with knowledge about the currently available parts and the product's state, processes can be rescheduled from their optimal order to an order that can be executed at the current time. In case feedback into preliminary phases of product creation may be challenging, e.g., due to the supply chain structure, approaches, as shown in [38], may be applied. Process quality optimization for jointing is performed "on the shopfloor" without design or work-preparation alterations using live geometric parts data. Digitalizing processes and products for feedback into design and use in later product lifecycle phases, on the example of the aircraft cabin interior, is proposed by the authors of [3]. Acquiring data in a product's digital thread for retrofit is especially important in aircraft manufacturing. Further, a live digital representation of the environment can aid not only in production but, e.g., in logistics [39]. As demonstrated by the authors of [35, 39], the benefits of standardizing interfaces, data models, and access to aggregated data from multiple domains are services — a new approach to value creation and optimizations in production.

4.3 Flexible, semi-automated production of aircraft interior components

First-tier suppliers carry out the production of aircraft interior components. The main components can be divided into cabin lining, e.g., side-wall and ceiling panels, and monuments, e.g., galleys, lavatories, hatracks, or partitions [40]. Because of their lightweight construction and sufficient fire, smoke, and toxicity (FST) properties, the cabin interior is primarily made from composite sandwich structures combining a NOMEX® honeycomb core and pre-impregnated glass-fiber face sheets. Their complex production process can be divided into the following steps [41]: raw panel layup, curing, machining, pre-assembly, and final assembly.

Since aircraft interior monuments are highly customized products, the varying processes throughout the production chain are countered by flexible but often poorly optimized manual labor. With growing demand and the recovering aircraft industry facing pressure from low-wage countries, the suppliers must enhance their productivity and product quality by increasing the level of automation (LoA) (Fig. 6).

The consistent end-to-end digitization of the process is the enabler for further increase in LoA. [21] introduces the concept of semi-automated interior components pre-assembly. Low-cost automation hardware such as projection systems or cobots is used to either support manual labor tasks or fully automate processes (s. Figure 6). Furthermore, the insert assembly as a high-volume task is fully automated by developing a robotic installation process [42] and practically investigating the required potting parameters [43]. [44] introduces an automation-friendly panel design, generating precise contours using potting compounds and a digital manufacturing process, leading to low tolerances. This is enabled by developing an automated, pressure-controlled potting process [45]. These approaches enable a digital and flexible manufacturing process and set a baseline for further assembly automation.

Integrational challenges

Integrating existing automation technology into assembly systems that were previously predominantly manual poses new challenges, mainly from different interfaces and missing standards between tool manufacturers. Although flexible hardware is more affordable than ever, the task- and product-specific programming and commissioning lead to high costs during implementation and operation, requiring a solution approach, e.g., consisting of an information model and a data transformation pipeline as introduced in recent works [46].

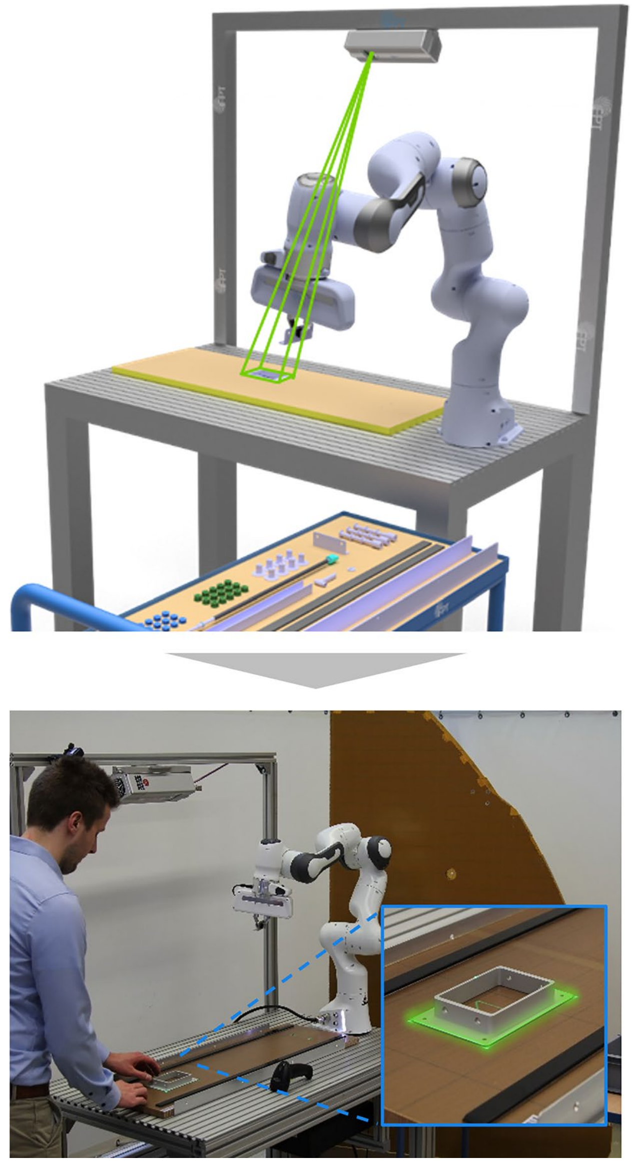

Fig. 6 The *Digital Production Process Twin* of an assembly station for hybrid assembly of cabin interior components (based on [21])

Digital assembly twin

Then, the information model is a basis for a generic assembly process forming a digital master, while the parametrization with real data instantiates a Digital Production Process Twin. Thereby, production planners or shopfloor operators are enabled to manufacture and plan customized cabin interiors flexibly. Besides, the digital process shadow contains the process's documentation reliably serving air authority regulations.

Fig. 7 Manual inspection process of an aircraft fuselage component with digital measuring equipment and assistance by head-mounted Augmented Reality (AR) glasses

4.4 Data acquisition and assistance in manual quality assurance and inspection processes

As a safety-critical product, quality assurance (QA) and inspection processes play a particularly important role in the lifecycle of an aircraft and its components. Two aspects characterize these processes: On the one hand, they are often carried out manually, and on the other hand, they are subject to a high level of documentation. Currently, utilized measuring equipment for inspection is mostly analog, e.g., calipers for checking geometric dimensions, preventing a direct digital recording resulting in paper-based documentation [47] (Fig. 7).

Organizational challenges: media discontinuities and demand for qualified staff

The manual transfer of paper-based data into digital systems creates media discontinuities [48], which is error-prone, often resulting in, e.g., transcriptional errors. In addition, the time gap between the acquisition of the data and the digital entry unnecessarily prolongs reaction times for countermeasures within the production process in case of errors. Regarding the aircraft, QA processes on large aircraft fuselage components usually require a wide variety and quantity of inspection methods, often causing additional errors due to false process order execution.

In addition to the deficits mentioned, QA and particular inspection processes are usually performed without additional assistance systems, so the success of process execution is tied to the expertise of the staff.

In summary, there exist two main deficits in manual quality assurance processes: insufficiently digitized measuring equipment and a lack of assistance systems. Currently, both of these inhibit the effective deployment of a digital quality assurance twin on the shopfloor.

Digital quality assurance twin

Two approaches enable the data flow of manual processes into a DT and ensure a correct data set, namely, replacing or updating analog measuring equipment with smart tools transmitting measured values directly, e.g., via protocols like MQTT or Bluetooth (e.g., shown in [49] for assembly processes). A prerequisite for the successful integration of devices is a flexible software environment that, on the one hand, handles the heterogeneity of the accumulated data and, on the other hand, is able to integrate the results into the digitally modeled QA process. A combination of multi-model databases, as presented in [50], and the use of IoT application platforms, such as in [50–53], represent a possible solution. Compared to conventional data acquisition systems (such as Computer-Aided Quality (CAQ) or MES), IoT application platforms have the advantage of extensibility and integration of different sub-applications. At the same time, information security has proven to be challenging in IoT systems and has to be addressed from the beginning when introducing them in production, especially when the acquired data is relevant for the safety of the product [54].

The previously introduced "Digital Quality (QA) Assurance Twin" replicates an inspection process, so it falls under the topic Digital Production Process Twin as per Fig. 2.

Integrating assistance systems

The next step in addressing the previously mentioned challenges is integrating assistance systems in the QA twin. Current state-of-the-art provides different solutions depending on the work area and the needed support function. The method of projection, e.g., laser projectors [55], moving head spots [56], or video projectors [57], usually covers different work areas but is restricted to indicating/displaying measurement locations and not verifying these.

In contrast, localizing the measuring tool, e.g., using an optical system with fiducial markers [58] or infrared tags [59], enables verification. Therefore, not only the digitally modeled measuring process is needed, but a digital replica of the production environment. Here, a data flow between the QA twin and possibly a further Production Process Twin is reasonable to prevent multiple data sinks.

With the help of the aforementioned enabling technologies, manual processes, and their information are digitized reliably. An example of a digitalized inspection process of a fuselage component is shown in Fig. 7 in which a handheld measurement device is used together with augmented reality glasses. In the shown example, the device allows a direct data flow to an information system, eliminating paper-based documentation. Furthermore, the use of augmented reality for large structures enables the inspector to find the correct inspection points and give instructions on how to conduct the inspection. Combining the manually acquired data with inspection data originating from other sources, e.g., from fully automated inspection stations, this entirety of data represents the "as-inspected" twin [60] of the aircraft. By linking the inspection data with information from other lifecycle segments, e.g., as-designed or as-built, a manufacturer can exploit potentials in the in-house and external value chain, e.g., the relationship to the commissioner. Such a holistic approach makes it possible to detect errors and uncover systematic causes, e.g., in the design or production of components. As a result, countermeasures can be initiated more quickly, and interdepartmental correlations are more likely to be identified. Another notable potential is that by integrating manual processes into the digital thread, knowledge from process experts can be captured and fed back to process planners (or other stakeholders), thus driving continuous process improvements. Due to the mere number of quality assurance and inspection processes required in aircraft production and maintenance, optimizations of these processes have great leverage.

4.5 Digital twins to enable AI-based identification of components in production supplying logistics

Despite recent advances in production process automation, most aircraft-related processes are handled manually, including, e.g., production supplying logistics [61, 62], where components are manually (de-)commissioned. Here, the identification of components is necessary to avoid misrouting and ensure subsequent correct assembly. With manual identification requiring domain experts and being costly, automated procedures are to be employed. While some components bear automation-suitable markers such as RFID tags, other components do not necessarily bear similar identifiers since they are not fit for flight, or the component bears mainly functional surfaces without the option to apply markers. In cases of retrofitting, part numbers (P/N) are often not readable since residues occlude them or they are worn out. Thus, in various processes, the use of visual identification of components is gaining in popularity [62–65]. However, most solutions depend on AI-based object identification procedures and, in turn, require tremendous amounts of training data. Manual acquisition of these data points is not scalable for use cases with a wide variety of components, such as the aircraft domain [66, 67]. A suitable alternative is the generation of synthetic AI training data based on virtual 3D-representations [63, 64, 68, 69], also applicable in production supplying logistic scenarios (Fig. 8). However, it requires suitable 3D representations of the to-be-identified components.

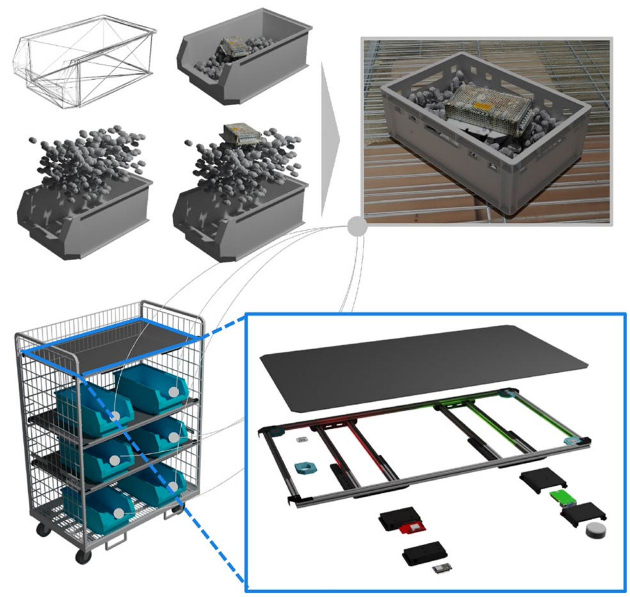

Fig. 8 Synthetic data generation to enable an AI application for the visual identification of components on a smart load carrier (based on [62, 68])

Compliance-related challenges

Currently, 3D representations of aircraft components are not shared across stakeholders. However, suppliers or OEMs have high-quality representations of their parts, as they are needed for primary production. However, without sharing these in high detail, they hinder the applicability of AI-based identification procedures and prevent the enablement of AI applications for various stakeholders along the lifecycle.

Collaboratively enabling an AI twin

One approach to overcome the data ownership issue is splitting the training based on compliance-critical data and the application at a third-party production facility, known in the context of federated learning [70]. For example, if one stakeholder creates an AI vision model as part of a DT — in this use case, a Digital MRO Process Twin — replicating the identification process, another stakeholder with access to the critical data can independently train the model, e.g., by creating synthetic data. So, the trained model enables the vision task, and the DT can be deployed somewhere at a third-party location. Since the technology does not allow for the extraction of critical product data back from the model, data ownership is assured. This collaborative approach, splitting training and deploying between different stakeholders, is easier to monetize or servitize than sharing the specific product data.

In retrofitting processes, another issue arises since 3D representations describe the components in an ideal state. However, after components are flown, they can experience discoloration due to heat exposure or aging. Thus, relevant features can change but are typically not included in the original 3D representations. Decentralized, regular re-training of the model, e.g., based on regular 3D scans, is then necessary to achieve the desired accuracy in the vision task.

4.6 Twins in cabin retrofit

Commercial aircraft cabins are modified during the aircraft lifecycle multiple times to meet customers' and airlines' changing requirements and needs. The main drivers are economic pressure to increase customer satisfaction and the airline's economic efficiency, e.g., by extending the in-flight entertainment systems and introducing additional seat rows. A cabin modification is composed of two parts: the planning and design (PD) and the modification and installation (MI) phase. A company's objective in conducting retrofit is to shorten the actual practical MI phase to let the aircraft back into operation as soon as possible. Therefore, a modification's extensive and laborious PD phase without access to the aircraft is the critical part mainly determining the project's profitability [71].

Data ownership and on-site acquisition
In related research [3, 72], missing data and information are derived that would significantly increase the reliability of the PD phase to prevent error-prone design and planning, resulting in unforeseen extended ground time. Currently, retrofit companies try to minimize the gap by buying missing dimensional information from other stakeholders as well as utilizing 3D scanning techniques. The first is costly and often not supported by third parties; the second solution is time-consuming and requires the aircraft's grounding.

Geometric as-is twin
On the one hand, these new resources can be derived from re-engineering processes based on 3D scanning (Fig. 9), but also other technologies like on-site augmented reality-assisted systems as proposed in [73] provide new data and information of high quality.

Scaling the concept of the geometric twin — in this case, a Digital Product Twin — from company-internal data and information reuse to external stakeholders inhibits its predominantly intellectual property regulations. A third-party trustee may regulate, observe, and approve the twin's incoming and outgoing data flows while ensuring a trusted, fair, cost-based data exchange. For example, critical data and information in cabin retrofit are 2D and 3D dimensional quantities of single airframe structures or even boundary representations of installed cabin monuments. The trustee can ensure that no intellectual property

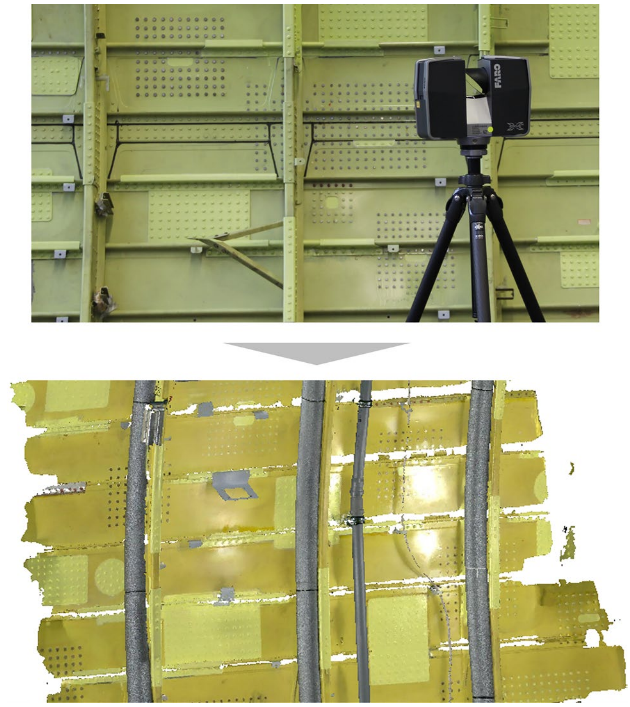

Fig. 9 3D scanning of a fuselage part to gather the as-is state, e.g., presence or position, of components like Brackets and Fittings (based on [3])

is violated by downsampling the data in quality and only including the necessary quantities. So, no complete 3D models or 2D technical drawings must be exchanged.

5 Core challenges in production and MRO

The main characteristics of production and MRO in the aviation industry, as defined in Sect. 3.4, lead to challenges in implementing and deploying DTs that we categorize into three different topics: integrational, organizational, and compliance-related. Figure 10 summarizes the main challenges of the previously given use cases that we will briefly discuss in the following in the context of the aircraft lifecycle.

5.1 Begin-of-life (BoL)

1. In the BoL, the market is similarly fragmented as in other industries, e.g., automotive. Numerous internal and external actors are in roles from product development to production and manufacturing. The main difference is that small batch sizes and no line assembly shape the production of the aircraft and its interior. The resulting low level of automation (s. Sect. 4.3) and, at

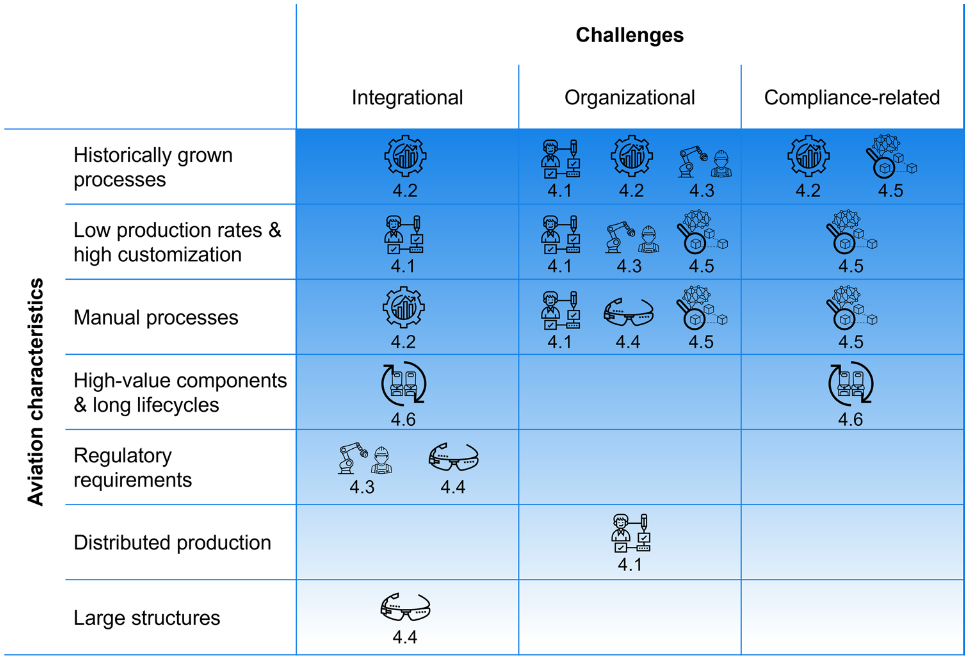

Fig. 10 Challenges in deploying Digital Twins in the aircraft production and MRO industry (referencing the given use cases; dense blue indicates areas of core issues)

the same time, many stakeholders (s. Sect. 4.2) have not favored the acceleration of standards development in recent years. However, the missing standards and semantics, as well as common interfaces, are the core issues that slow down the deployment of DTs. Recent industry efforts, as already mentioned in the introduction of this work, like Gaia-X and the IDTA, are the first step into breaking the current interoperability barriers.

2. Besides standards and interfaces for connection assets on the shopfloor, historically evolved design and development processes during product creation lead to different design tools in this phase that again barrier a subsequent homogeneous interconnected software environment. Especially in the assembly planning of individual components, as in the aircraft industry, these issues prevent a consistent data flow between the two steps (s. Sects. 4.1 and 4.3) and thus also modeling the Digital Master.
3. While integrational challenges mainly affect data, information, and knowledge exchange between internal and external actors, direct organizational challenges usually address the manual labor in aircraft production that complicates the data flow between the real product/process/resource and the digital replica. The use case in Sect. 4.4 reflects this deficiency while also underlining the scalability of a DT replicating a manual process, significantly increasing the process's reliability.

5.2 Mid-of-life (MoL)

1. Besides most of the challenges from the BoL, with the aircraft's longevity character, a lot of data and information are, on the one hand, digitally not available but also distributed across stakeholders. So, as outlined in Sects. 4.5 and 4.6, acquiring the as-is state is a typical task in the MoL. Albeit imaging the product or component in its current condition, semantics, and occluded details are not included. Here, knowledge of the products from the BoL is important to derive the geometric as well as semantic as-is state to instantiate or update a DT.
2. During the MoL in maintenance, retrofit, and remanufacturing, the batch size is predominantly one. That means increasing the automation of processes needs hybrid and flexible real and digital solutions. Besides the already mentioned complex real-to-digital data flow, models must be much more generic to be reconfigurable (Sect. 4.3).
3. MRO companies must act globally to fulfill the requirements of time-critical corrective actions in maintenance. Currently, companies solve this by traveling and distributing experts. However, digitizing the processes and human knowledge into a DT will be an enabling technology in the future.

6 Summary and outlook

The digitalization of products and processes to deploy DTs in the aviation production and MRO industry faces many barriers and issues, especially of integrational and organizational nature.

Numerous internal and external actors share the product creation and the life-extension market. Since each of them has to map individual characteristics of their often historically grown production processes, different data management systems co-exist. Due to the high heterogeneity and divergent requirements, holistic integration into a superordinate DT is not feasible with the available information systems. Besides the technical aspect, compliance-related barriers counteract even the connection of individual data sinks or twins.

Instead, this work showed that purpose-bound and domain-specific data and information could be aggregated, mapped, and replicated in individual DTs. These enable the streamlining of individual development, planning, and production processes as outlined in the use cases.

The subsequent step to gain further added value must be the interconnection through standardized interfaces of these individual twins, empowering concurrent engineering and enhanced data exploitation for applications such as predictive maintenance.

Current research and development activities on DT application concepts in aircraft production show that the industry faces a massive amount of work to reach a higher level of digitally replicating tangible and intangible assets. The required tools and methods must additionally be transformatively integrated into historically grown processes. Federated learning, external data trustees, or the Gaia-X initiative are approaches to overcome such compliance-related challenges. Digitalization initiatives at the big companies, like Airbus' *Digital Design, Manufacturing & Services (DDMS)*[5] or Lufthansa Technik (LHT)'s *Digitize the Core* are promising projects in transforming the industry and envision the application of results from current research but also demanding further one. In a recent statement, LHT stated that they are working on a triple-digit number of single projects under the named initiative.[6] In conclusion, as we outlined in this work's use cases, taking the proper steps toward enabling DTs can lead aviation into a more anticipating, agile, productive, value-adding, and sustainable future.

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[5] https://www.airbus.com/en/innovation/disruptive-concepts/digital-design-manufacturing-services

[6] https://www.lufthansa-technik.com/en/pr-lufthansa-technik-posts-record-result

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Declarations

Conflict of interest The authors have no Conflict of interest to declare that are relevant to the content of this article.

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