# INDUSTRY 5.0 IN AIRCRAFT PRODUCTION AND MRO: TECHNOLOGIES, CHALLENGES, AND OPPORTUNITIES

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## Abstract

Globally interconnecting machines, processes, and resources driven by exploring and advancing new technologies defined Industry 4.0, resulting in, e.g., Cyber-Physical Production Systems (CPPS). The aircraft industry particularly struggled with transforming production and Maintenance, Repair, and Overhaul (MRO) processes, replacing humans with machines, and automating as well as digitizing significant parts of their value- and non-value-adding activities. However, given current societal and environmental challenges, future industries must change from technology-driven only to value-driven, working sustainably with resources, including human capital, the idea behind Industry 5.0. On the one hand, the aircraft industry challengingly faces these demands since even Industry 4.0 concepts and technologies are not fully exploited or implemented; on the other hand, due to the specific aircraft production and MRO as well as the environmental impact characteristics of the product, tremendous potential arises regarding placing human well-being back into the core of adding value, decreasing environmental footprint, while building a resilient and fortified industry against disruptions of this era. In line with the Industry 5.0 terminology, in this work, we outline the objectives, challenges, enabling technologies, and opportunities for sustainable, resource-efficient, human-centric, and resilient concepts, systems, and procedures in aircraft production and MRO.

**Keywords**
Industry 5.0; Aircraft; Production; Manufacturing; Maintenance; Repair; Overhaul; Logistics

## 1. INTRODUCTION

The fourth industrial revolution was defined by the need to globally interconnect machines, processes, and resources, increasing productivity and, thus, prosperity. Ten years after the term Industry 4.0 (I4.0) was more widely used, introduced at the Hannover Messe 2011 [1], the European Commission (EC) exclaimed Industry 5.0 (I5.0) in an effort to force current industries to reposition their roles in society and explicitly consider current global environmental challenges [2]. While Industry 4.0 is technology-driven, the proactive exclaimed Industrial Revolution 5.0 is value-driven – supposed to be a technology transformation with a particular purpose.

Up to now, authors, administrative bodies / authorities, and governments across the world have interpreted the term I5.0 differently. However, according to the EC, I5.0 is shaped by human-centricity, sustainability, and resilience (s. Figure 1) [3], incorporating the idea that industries need to become increasingly value-driven in addition to technology-driven, working sustainably with resources, including materials and human capital, respecting the production limit of the world, and societal objectives beyond jobs and economic growth.

**FIG 1. Core values of Industry 5.0 [4].**

The aircraft production[1] and Maintenance, Repair, and Overhaul (MRO) market shared by design, manufacturing, and maintenance organizations, according to EASA 21 J/G and 145 [5], respectively, is mainly dominated by diverse manual, non-digitized processes resulting in low levels of automation [6]. Despite recent I4.0 technologies and advantages in the last ten years, the introduction of these into the aircraft production industry remains limited. The main challenge that inhibits the implementation of service-oriented

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[1] In this work, we define the ambiguous terms *production* and *manufacturing* as follows: As in German, we differentiate between the two. *Manufacturing* includes the processes around transforming raw materials and creating physical workpieces, tangible goods, or other discrete assets. We understand manufacturing as a technology-focused process step. In contrast, *production* is the superordinate term involving all processes of making a consumable good or capital asset, including all activities from manufacturing, assembly, logistics, finance, etc..

architectures or intelligent, self-organized Cyber-Physical Systems (CPS) is missing digital consistency caused by historically grown processes, strict regulations, challenging system complexity, small lot sizes/production rates, and mostly manufactory production and site assembly characteristics. Thus, most processes are still performed manually throughout the supply chain and throughout the aircraft's lifecycle [7], e.g., manufacturing aircraft interior [8, 9], inspection [10, 11], or assembly [12].

Due to the named aircraft production characteristics, the industry can pioneer implementing I5.0 ideas. On the one hand, fully automated production processes to eliminate human participation are not feasible, primarily due to strict regulations and the aircraft's individual, long-livity characteristics. On the other hand, aircraft are significant contributors to carbon emissions and environmental pollution, making the potential of deploying sustainable technologies and concepts particularly high. Moreover, as seen during the COVID-19 pandemic, the aircraft industry is specifically vulnerable to non-influenceable disturbances [13]. In line with the terminology and ideas behind I5.0, we aim in this work to use case-driven outline the objectives, elaborate on the core characteristics, challenges, and enabling technologies / concepts for sustainable, resource-efficient, human-centric activities in the aircraft's different lifecycle phases.

The rest of this work is structured as follows: First, we revisit the industrial revolutions from 1.0 to 4.0 in Section 2. Then, in Section 3, we outline industry-neutral the different I5.0 definitions, characteristics, and enabling technologies. Afterward, we describe the discrete production steps in an aircraft's lifecycle while motivating the need for I5.0 in this industry (s. Section 4). We continue in Sections 5, 6, and 7 with use cases for manufacturing, intralogistics, and MRO, respectively, and outline in these I5.0 technologies, challenges, and opportunities. Subsequently, we summarize in Section 8 and finally discuss and conclude the results and findings of this work in Section 9.

## 2. INDUSTRIAL REVOLUTIONS 1.0-4.0

### 2.1. Industry 1.0 to 3.0

The 1st Industrial Revolution is characterized by the spread of the first mechanical working machines powered by water or steam (s. Figure 2 for the industrial revolutions timeline). A central invention of this time was the mechanical loom, which Edmond Cartwright developed in 1784 [18]. It marked the beginning of Mechanization, which at the time helped to provide the population with clothing and food, as productivity was drastically improved. The focus of the 2nd Industrial Revolution was the introduction of mass production based on the division of labor through electrically driven assembly lines. The first conveyor belt used in the slaughterhouses of Cincinnati around 1870 represents the beginning of this period. Later, the concept was adopted and further developed into assembly lines by Henry Ford in the automotive industry, eventually for large-scale industrial mass production of goods in the electrical and chemical industries. In the 1960s, the 3rd Industrial Revolution followed, primarily characterized by the increasing use of automation solutions, made possible by Programmable Logic Controllers (PLCs). On the one hand, this significantly streamlined processes, and on the other hand, plants were now able to mass-produce different product variants. At this time, the market changed from a seller's to a buyer's market, as industrial companies could no longer assume that they would be able to sell their entire production on the market. Customers' wishes became increasingly individualized, and factors such as quality and uniqueness became more important [19].

### 2.2. Industry 4.0

The I4.0 developments refer to the increase of networking in production, which is technically driven by CPS in a communication infrastructure of the Internet of Things and Services [20]. [21] discussed the key concepts of I4.0, which can be summarized as follows:

- Service-oriented reference architecture
- Intelligent, self-organizing Cyber-Physical Production Systems (CPPS)
- Interoperability between CPPS and humans
- Adaptability and flexibility to changing requirements
- Optimization for Overall Equipment Effectiveness
- Data integration across disciplines and entire life cycle
- Reliable and secured communications between businesses
- Data security

## 3. INDUSTRY 5.0

The term Industry 5.0 – in short, integrating societal goals and sustainable practices into the producing industry – has emerged in response to the current challenges of societies and industries. Industry 4.0 is characterized by technology-driven advancements, such as the Digital Twin (DT) concept and Artificial Intelligence (AI), aimed at enhancing production efficiency and flexibility. In contrast, I5.0 complements these technological advancements, focusing on value-driven principles [22], e.g., principles of social justice and sustainability [23]. Exploring the distinction between I4.0 and I5.0, it is essential to note that I5.0 is not a substitute or successor to I4.0 but rather a progressive, expansive approach. It is an umbrella term for extending the I4.0 thoughts, enriching them with novel ones facing the challenges of our time. Essentially, it tries to answer how industry and the latest social and environmental trends and requirements can or must co-exist in harmony [24]. At the ten-year mark of I4.0, in 2021, this idea was taken up by the European Commission (EC), recognizing the importance of repositioning the roles of European industries in society and the environment, aiming at advocating the ideas in research and development to strengthen the industrial landscape [4].

### 3.1. Fundamental Blocks

Before the EC officially defined the term, definitions with slightly different pronounced characteristics co-exist in literature [22], either focusing more in detail on the human-centricity part/human-robot co-working [25–27], novel technology [28], or outlining that the interweaving of both is necessary – when intelligent devices, systems, and automation co-operate with human intelligence and their knowledge [19]. But the majority of the authors rethink the position of the human part in the production industry. The EC further extended these thoughts and unified three fundamental blocks under the term I5.0: human-centric, resilient, and sustainable (s. Figure 1).

#### 3.1.1. Human-centric

Previously revolutions were always driven by the conception of separating the machines from the humans (s. Fig-

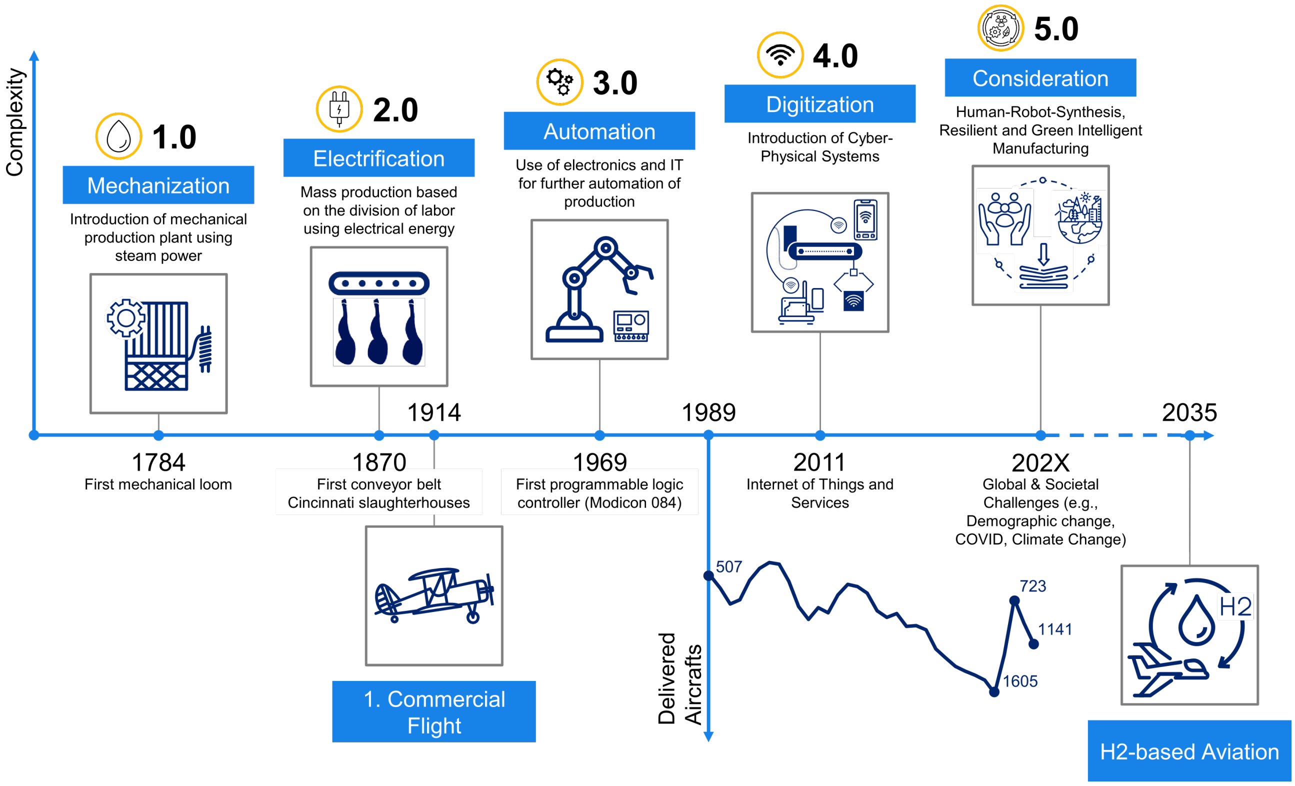

**FIG 2.** **Milestones from Industry 1.0 to Industry 5.0, first commercial flight, combined Airbus and Boeing commercial aircraft deliveries, and Airbus' H2-based aviation goal (based on [2, 14–17]).**

ure 2), resulting in advanced robotics even converging into humanoid robotics – in an effort to try to mimic human behaviour; in contrast, I5.0 places the human and its universal skills and intelligence back into the core centre, humans and machines should work in co-existence [27]. Authors even extend terminology, e.g., speaking of Human-Cyber-Physical Systems (HCPS) referring to including the human in the cyber-physical interaction loop [23, 29–31] or Human Digital Twins (HDT) naming digital twins of humans [23, 32]. The I5.0's human-centric idea is not only to utilize a human operator's skills and knowledge with the objective of increasing productivity, e.g., designing flexible production systems by incorporating Human-Robot Collaboration (HRC) or corporation, but supporting the individual human needs and interests by machines, placing the operator's welfare at the core. Instead of inquiring about potential applications given a novel technology, according to the EC [3], industries must question what technology can do for us - leveraging technology in order to tailor the production systems to the worker's requirements. Concluding, I5.0 promotes *talent, diversity and empowerment* [4].

### 3.1.2. Resilient

Crisis and technological advances in this century showed that production systems can not be built without being modified or retrofitted for years. Here the fundamental I5.0 block resilience denotes the imperative to enhance the robustness of production systems, fortifying them against disruptions and ensuring their capability to furnish and sustain critical infrastructure during periods of turmoil [3]. Therefore, Industry 5.0 must be *agile and resilient* based on flexible and adaptable technologies [4]. Industry 4.0 focused on long, globalized, connected value and supply chains, cost-effective and efficient, which foundations have been shaken during instances of geopolitical realignments and natural calamities, especially during, e.g., the COVID-19 pandemic. It underscored the vulnerability of our existing paradigm of globally interconnected production – particularly crucial in instances where value chains are instrumental in meeting fundamental human necessities, e.g., healthcare and security. An approach here is not a form of deglobalization but a rethinking of rigid and inflexible chains – a reevaluation of prevailing work methodologies and strategies combining flexibility with resilience to tackle vulnerabilities – as shown during the COVID-19 pandemic – effectively.

### 3.1.3. Sustainable

The limits set by our planet's boundaries are reached year after year; industries must respond here and embrace sustainability [3]. Industry 5.0 leads to action on *sustainability and respects planetary boundaries* [4]. This entails establishing circular procedures summarized under the nine *Rs* [33]: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, and recycle – minimizing waste and environmental repercussions. Sustainability involves curbing energy usage and emissions to prevent the depletion and deterioration of our natural resources while also fulfilling the requirements of the present generation without compromising those of the generations to come. Fulfilling sustainable goals through implementing a circular economy varies in complexity across industries and already embodied practices [34]. [35] name here Greenintelligent Manufacturing (GIM) – a transitional paradigm that describes the necessity of merging intelligent, e.g., Industry 4.0 and green technology; in short, intelligent techniques enable green/sustainable objectives.

### 3.2. Enabling Technologies

According to a workshop with industry leaders organized by the EC, six different core fields of technologies support the concepts and ideas of I5.0 [2]:

1) **Human-centric solutions and human-machine-interaction** technologies that interconnect and combine the strengths of humans and machines.
2) **Bio-inspired technologies and smart materials** that allow materials with embedded sensors and enhanced features while being recyclable.
3) **Real time-based digital twins and simulation** to model entire systems.
4) **Cyber-safe data transmission, storage, and analysis technologies** that are able to handle data and system interoperability.
5) **Artificial Intelligence**, e.g., to detect causalities in complex, dynamic systems, leading to actionable intelligence.
6) **Technologies for energy efficiency and trustworthy autonomy** as the above-named technologies will require large amounts of energy.

Each of these do not exclude themselves or exist independently. Facing the complexity of I5.0 challenges they are to be superimposed. We will use the same taxonomy in the following of this work.

## 4. AN OVERVIEW ON AIRCRAFT PRODUCTION

With a typical lifespan of 25 years for passenger aircraft and even more for freighters [36], the product lifecycle of an aircraft consists of multiple repetitive development and production cycles, as shown in Figure 3. After the initial first flight, the aim of activities in Maintenance, Repair, Overhaul (MRO), retrofit, and remanufacturing is always to ensure the airworthiness and profitability of the aircraft.

### 4.1. Begin-of-Life (BoL)

Production of a new aircraft involves manufacturing, logistics, assembly, and testing processes on many different system levels. As product development is required to follow certain process guidelines such as the SAE ARP-4754 [37], and systems are still developed separately according to the ATA 100 chapters or its successor, the S1000D standard [38], also the production of systems, subsystems, and components is often carried out independently. Thus, most components are manufactured and pre-assembled made-to-order by numerous different suppliers around the globe before being integrated into the aircraft in the final assembly line [39]. Production and assembly planning, as well as external and internal production-supplying logistics, are thus a highly complex but integral part of aircraft production, however, depending on a complex global supply chain. High variety in systems such as the aircraft cabin, where each customer has different requirements and layouts, further increases the complexity of planning and production tasks, resulting in multiple planning iteration loops and long production ramp-ups [40]. Therefore, and due to the comparably high tolerances, large parts, and low production volume, manual work dominates in aircraft production, and final assembly is rather of field than of line assembly type [39, 41]. All development, production, and testing processes need to be qualified, documented, and monitored by relevant authorities, OEMs, and customers to ensure the safety of the aircraft [39].

### 4.2. Mid-of-Life (MoL)

The aircraft usage phase is characterized by repeated MRO cycles. Mandatory checks and preventive maintenance procedures are performed by airlines or MRO contractors according to prescribed intervals [42], ensuring safe operations at all times. Checks ranging from on-wing engine borescopy [43] to the detection of smallest cracks in dismounted engine components [44] are each conducted by trained experts. Advanced predictive maintenance efforts are often hindered by the limited availability of data, which is spread across different stakeholders and often not available in digital and contextualized form [6]. If problems are detected or failures occur unexpectedly, corrective maintenance aims at resolving the faults as soon as possible by installing new parts or repairing defects. However, the availability of skilled maintenance personnel and replacement parts can be limited, especially when defects occur at remote locations, and experts need to travel and/or parts have to be shipped to the site [6]. Defective or deteriorated high-value components such as engine blades are, if possible, remanufactured to meet serviceable limits again [39]. Thereby, as each defect is different, processes such as machining are either conducted manually, automated processes are repeated until success is detected by an operator, or programs are individually adapted [45, 46]. Due to the longevity of an aircraft, retrofitting activities are of special importance to provide passengers and crew with up-to-date technologies, services, and hardware or to change the purpose of an aircraft, e.g., to convert it into a freighter [47]. Again, those activities require adequate planning, logistics, quality assurance, and documentation.

### 4.3. End-of-Life (EoL)

If an airframe is finally out of service, disassembly and scrapping are conducted by specialized companies. Whole systems such as engines or single components such as cabin elements might still be reused in other aircraft after refurbishment, kept as spare parts, repurposed, recycled, or sold as collector's items [48].

### 4.4. Key Characteristics

Summarizing the previously given overview of production activities along the aircraft lifecycle, we note the following characteristics (following [6]):

1) Manual processes, since the low production volumes and a high degree of customization due to customer-specific configurations make conventional automation approaches too complex, expensive, and mostly infeasible;
2) Dependence on expert knowledge (e.g., classifying defects) and reliance on manual processes due to regulatory requirements;
3) Due to the high value and long lifecycles of an aircraft, efforts are made to maintain, remanufacture, reuse and retrofit systems, subsystems and components;
4) On-site final assembly due to large structures and the multiple hierarchy levels of assembly;
5) Historically grown processes that meet both political requirements and globally dispersed stakeholders;
6) Distributed production with a large number of suppliers providing modules, systems, and components for the complex product system aircraft;
7) Aviation authority regulations and the criticality of aviation safety lead to high levels of inspection, testing, oc-

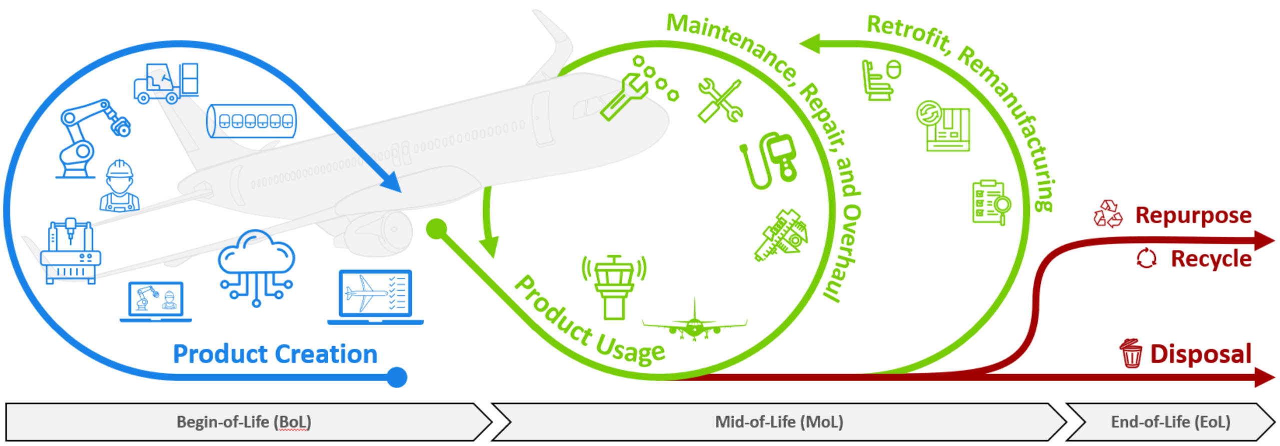

FIG 3. Activities in an aircraft's lifecycle (based on [6]).

cupational health and safety, certification, and documentation.

### 4.5. Industries 1.0 to 4.0

The above characteristics have not significantly changed over the last decades. Since the first commercial flight in 1914, different product innovations have been established on different system levels, such as digital fly-by-wire technology or carbon fiber (CF) fuselages (s. Figure 2). However, disruptions, e.g., fully automated line production, as in the automotive industry, have not been implemented in aircraft production, especially point 7) (s. above) results in conservatism against innovations. Thus, the base product and the general boundary conditions remained. Therefore, after mechanization in Industry 1.0, no typical line-type mass production of Industry 2.0 and only a low level of automation (Industry 3.0) was introduced. In recent years, long after the automobile or consumer electronics production, efforts were made to introduce automation in some processes such as CF prepreg layup [49], cabin interior production [50], and the fuselage assembly [51]. At the same time, Industry 4.0 approaches began to make inroads into aircraft production. These mainly include digitization, data integration, and networking, which are, however, still on a low level compared to other industries [6]. In the context of I4.0, moves are additionally made to research and implement model-based systems engineering in product development and production planning [40, 52], information security measures in IIoT-based manufacturing [53], human-robot collaboration in assembly [54], augmented reality in maintenance [55], and artificial intelligence in inspection tasks [56], as will be elaborated in specific use cases in Sections 5 to 7.

### 4.6. Motivation for Industry 5.0

The need for a faster transformation and implementation of new technologies and measures in aircraft production has increased over the last few years. With its globally distributed supply chains and the nature of the product as a transport medium, the aircraft production industry is especially vulnerable to disruptions and crises worldwide, for instance, the COVID-19 pandemic. Boeing and Airbus combined commercial aircraft delivery rates tripled from 1989 to pre-pandemic, but fell to less than a half in 2020 (s. Figure 2). Currently, the world passenger volume has revived year after year, but the aircraft delivery still did not recover fully. Socio-economic factors such as demographic change lead to a shortage of qualified personnel, on which aircraft production is especially dependent due to its unique characteristics. Finally, climate change became ubiquitous. Due to the high impact of aviation on the climate, ambitious but necessary goals in fossil fuel emissions reduction were set, which paved the way toward an actual disruption: the development of an entirely new, hydrogen-powered aircraft by 2035 [57] (s. Figure 2). This bears the opportunity to co-design products and production for the first time to allow for the expedient introduction of Industry 3.0, 4.0, but also 5.0 measures in aircraft production. Thus, not only the aircraft itself but also its production can and must become more sustainable, resilient, and human-centric. The following sections will elaborate on enabling technologies, implementation measures, and opportunities.

## 5. MANUFACTURING

Manufacturing activities in highly complex commercial aircraft production are multifaceted, including typical forging, forming, casting, and machining processes in fabricating, e.g., fuselage, wing, or engine parts. A variety of metal and non-ferrous metal alloys are used here. These heavy-weighted materials were first replaced to a large extent in the A380 and Boeing 787 during the early 2000s. The 787 carries a reportedly 50% carbon/epoxy airframe structure [58], saving up to 17% fuel [59]. However, an aircraft requires an assortment of materials and manufacturing processes on the finer to the larger scale. Besides fabricating the individual parts, assembly is the most important and time-consuming production activity with more than 50% of the workload [60]. The airframe structure assembly has different levels, starting with fuselage section parts and ending in marrying the overall fuselage ton and wings [61]. Third-party companies design, manufacture, and fully assemble engines, interiors, and avionics, while propulsion system-relevant, landing gear, and other electrical, hydraulic, and pneumatic systems are typically pre-assembled at Airbus or Boeing production facilities. The final assembly is mostly done manually, where most of the value-adding activities are conducted inside the aircraft. (Off-site) pre-assembly is based on the dimensions, narrow accesses, and individual configurations difficult. Following the assembly tasks, inspection for Quality Assurance (QA) is an integral and highly important activity since the aircraft is of critical characteristic.

The human-conducted or machine-assisted activities in aircraft manufacturing are specifically relevant to Industry 5.0

ideas and concepts, resulting in six individual use cases in the following sections. Differently, the first deals with Additive Manufacturing (AM), targeting the Industry 5.0 sustainable and resilient ideas.

### 5.1. Smart Materials and Bio-inspired Technologies through Carbon Fiber 3D-Printing

Carbon fiber composites have long represented a promising material for aircraft production due to their low weight and high stiffness and strength [62]. This lightweight material poses its own challenges for manufacturing complex parts with high curvature, as the fibers are most often woven into fabrics, that have to be laid up into expensive molds [62]. This common production method also makes it hard to fully facilitate the anisotropic property of the composite material [63]. With the additive manufacturing (AM) method of Fused Deposition Modeling (FDM) the possibility of placing singular fiber strands is opened up, while also not requiring molds and enabling structurally optimized parts to be manufactured [63].

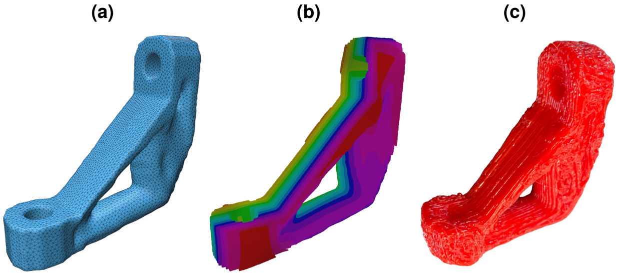

**FIG 4. (a) Optimized topology. (b) Non-planar slices. (c) Manufactured part.**

By being able to inlay copper wires or even use the carbon fibers themselves as conducting material, smart materials can be realized with this manufacturing method. Furthermore, the structural optimization process oftentimes result in bio-inspired geometries. An example for this can be seen in Fig. 4. This multi-dimensional manufacturing is supported by novel methods in FDM, where additional movement freedom enables the fibers and wires to be placed out-of-plane and in the direction of load and current distribution and information flow. The method of non-planar printing in combination with varying the layer height requires new slicing and pathplanning methods that make use of the increased degrees of freedom [64, 65]. Carbon fibers are also able to be recycled [66], making this process an important realization of I5.0 manufacturing.

Regarding the central goals of I5.0, the possibility of rapid and dynamic manufacturing using AM represents an important part of achieving resilience in manufacturing. Rapid prototyping can accelerate the development of substitutes. AM as a whole opens up new possibilities with the advantages of material diversity, design freedom, reduced lead times and on-demand production. Additionally, printing machines are widely available and easily configured due to the open source nature of many important projects in the past and foreseeable future. To achieve sustainability beyond recycling, AM enables efficiency gains in production and operation by promoting localized production resulting in reduced logistics emissions, lightweight construction and material diversity, that enables the use of ecological and biodegradable materials. Finally, AM requires a workforce with a combination of technical skills and creativity, including design for AM, machine operation, and post-processing. All of the reasons stated above establish the relevance and applicability of AM for the topic of I5.0, with the central focus being on the state of the art in 3D printing, like multidimensional printing and non-planar carbon fiber AM.

### 5.2. Skill-independent Augmented Reality (AR)-assisted Robot Programming

Integrating robotic automation within aircraft manufacturing, especially in the final assembly, presents various challenges. Due to a substantial level of customization, limited availability of digital models, and size-scaling tolerances, traditional mass-production-oriented robot programming strategies cannot be used efficiently. A potential solution stems from the utilization of Augmented Reality (AR) assisted robot programming (s. 5). With AR‘s ability to freely combine digital and real content in interactive interfaces, classic features of offline programming systems can be transformed and employed to create more efficient shopfloor-near robot programming systems [67].

**FIG 5. AR-assisted robot programming in aircraft fuselage manufacturing.**

As a medium, AR is not limited to a specific setup and can be implemented using a diverse range of technologies and adapted to various applications. This designability addresses the challenges posed by the ongoing demographic change, as it enables developers to not only use AR as a means to increase the efficiency of workflows but also tailor application design and process execution tightly to each individual user’s skill level and specific requirements. Such personalized interfaces have the potential to elevate job satisfaction, reduce frustration, and lower skill requirements. This creates accessibility to the complex area of industrial robot programming, especially to individuals with varying levels of expertise or other limitations that are challenged by standardized interfaces and workflows.

The primary challenge that needs to be addressed in the scope of I5.0 centers around establishing a comprehensive understanding of how AR applications can be customized to different human users. That entails harnessing their specific skills and knowledge while ensuring plannable and secure outcomes of executed tasks. An additional challenge originates from the necessary software development effort to create these personalized user interfaces. It is required to comprehend how various types of different AR technologies, especially in the areas of visualization, interaction, and tracking, can be efficiently combined and presented to a diverse user group.

### 5.3. Augmented Reality (AR) Leakage Inspection for Hydrogen Aircraft Systems

Due to insufficient technological capabilities for the electrification of aircraft engines, hydrogen will play a significant role in the decarbonization of the aircraft industry in the upcoming decades. Hydrogen is odorless, extremely flammable, and has the capacity to escape through even the smallest cracks due to its dimensions as the smallest element. Regular leak inspection of components conveying hydrogen is an important core competence, especially in aviation, in order to ensure safe assembly, operation, and maintenance. The limited accessibility, dimension of aircraft components, and the unstable behavior of leakage gas flows require manual measurements as automatization is technologically complex, inflexible, and cost-intensive. However, manual leakage testing is time-consuming and strongly dependent on the inherent user knowledge of the individual technician. All components are tested according to a standardized procedure with a pressure drop test, a soap bubble test, and finally with sniffing devices. Electrochemical sniffer devices measure the hydrogen concentration only at specific points in the sensor and can be equipped with suction devices. The process control is complex because the sensor can only detect gases with a delay resulting from the sensor principle and the duration of the gas transport from the intake to the sensor surface [68]. The integration of augmented reality (AR) systems can assist humans in the inspection process with additional digital information and complements employees' flexibility and individual knowledge. AR glasses overlay real machine parts and measuring equipment with 3D animations combined with metaphors to provide sensor guidance to the scenario. It facilitates a more efficient inspection process to make use of optimized process execution, documentation, and quality of data acquisition with full utilization of both hands. The AR leakage application helps users identify the correct components, maintain the correct sensor process speed, and provide final documentation of the measurement process.

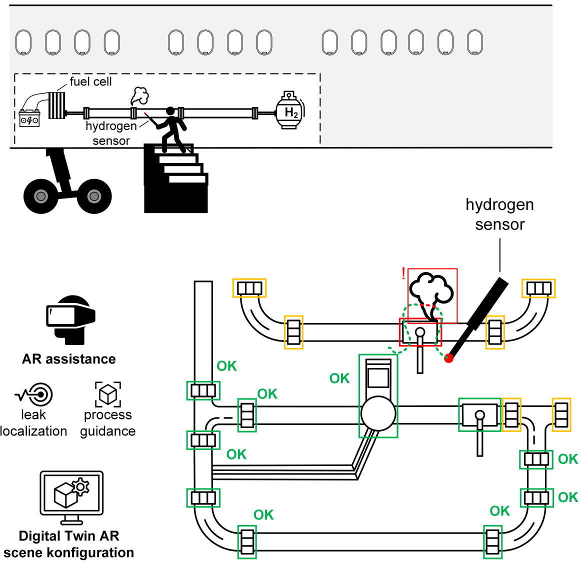

**FIG 6. AR-assisted leakage inspection on aircraft components.**

Application development includes adapting existing AR hardware, tracking methods, UX guidelines, and communication interfaces. A rapid development of new hydrogen systems and product variants for aircraft is to be expected (fuel cells, H2 combustion turbines, ...), which leads to a high demand to adapt AR applications for each new product design. There is a need for authoring systems that allow augmented reality systems for leak inspections to be configured with digital models, metadata, and domain knowledge with as minimal specialized knowledge as possible [69]. For the highly automated creation of AR applications in aerospace, 3D CAD data of aircraft and hydrogen components can be used. These are combined with defined metadata in the modeling language (AML) and the manual definition of trajectories through the use of AR hardware on the respective components. Captured process data can be used to improve the inspection process due to usability and the Integration of tracked operator decisions over various inspection cycles. The high level of digitization and data quality enables the inclusion of instructions for error-prone components and provides valuable feedback for the design of the inspection procedure.

### 5.4. Flexible, Robust Assembly of Aircraft Interior Components

Aircraft interior components, made from lightweight composite materials, are highly customized products since they are used as a unique feature to differentiate from competitors. The assembly of the broad range of variants is often met with manual processes. Current research and development investigate how some of the processes can be automated or supported to meet the increasing production rates. Automation hardware such as cobots or assistance systems such as projection devices enabled a flexible and semi-automated assembly in the form of CPS [54]. Furthermore, the commissioning of that hardware can be supported by using models of the processes and resources [70].

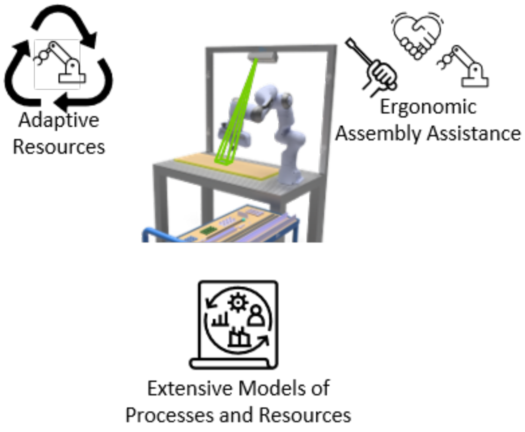

**FIG 7. Robust, flexible assembly represents values of I5.0 based on [54].**

With regard to I5.0 technologies, individualized human-machine interaction can already be achieved, and data transmission and storage technologies allow the creation of even more extensive models. So far, the objective of the approaches described above was the increase of productivity to meet the growing demand for passenger aircraft. However, using semi-automated assembly systems can also be seen from a human-centric perspective, improving ergonomics by reducing repetitive tasks and supporting unskilled workers with unfamiliar tasks. Furthermore, the assembly-specific models allow a quick reconfiguration and adaptation of existing resources to new products that result in a more resilient production. Customization, in this case, is not only customer-driven but also a result of continuously changing product design, resulting in more lightweight construction to reduce the environmental impact of the aviation industry by reducing specific fuel consumption. This can be met with flexible, hybrid assembly systems, adding not only economic value but also enabling more ecological production with human-centric technologies (s. Figure 7).

### 5.5. Human-Action-Recognition (HAR)-based Progress Detection in Manual Assembly

Arising from the use case described in Section 5.4, the flexible assembly of aircraft interior components, the investigation of manual assembly processes for multi-variant products is an important part of Industry 4.0 considerations [71]. Here, efficiency and flexibility can be increased by introducing Human-Robot Collaboration (HRC).
HRC embodies the synergy between human workers and robotic systems in a shared operational environment. Central to this collaboration is the cultivation of mutual awareness – a dynamic interplay where humans and robots understand each other's capabilities, intentions, and actions. Humans gain insight into the robot's real-time status, intentions, and potential areas of assistance. Simultaneously, through advanced sensors and communication interfaces, robots can decipher human movements, expressions, and verbal cues, allowing them to anticipate and respond to human needs more effectively [72]. Such a communication channel from the human to the machine is developed based on optical movement tracking and Human-Action-Recognition (HAR) methods to avoid non-value-adding activities for the worker, e.g., performing gestures to confirm completed process steps [71]. A HAR-ready workbench is depicted in Figure 8.

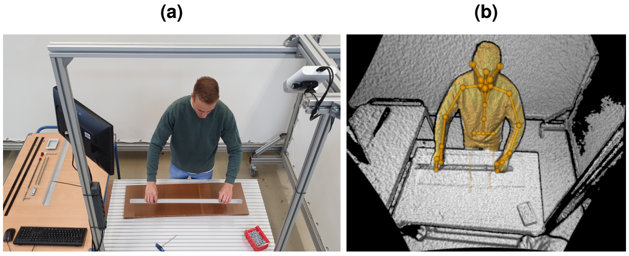

**FIG 8. (a) Workstation with Azure Kinect for multi-variant assembly processes in aircraft interior production. (b) Azure Kinect depth image and skeleton reconstruction. [71]**

Motivated by key contents of I4.0, the aforementioned HAR method to detect the assembly progress non-invasively is an important contribution towards the goals of I5.0. The heightened mutual awareness fosters a safer and more productive collaboration, where each participant's strengths are leveraged to optimize task execution, problem-solving, and overall operational efficiency. Thus, this method is to be assigned particularly to the I5.0 keyword 'human-centric'. It enables a non-invasive process observation, which does not distract the worker's flow and integrates the human into the digital process twin. As a result, the HAR methodology is an enabler for individual configurations of the workplace and robot programs and also provides human-individual process flexibility to adapt to different skill levels and preferences. Furthermore, optical assembly tracking and HAR can be used to monitor ergonomics and increase operational safety, especially in collaboration with robots. That is attributable to the keyword 'human-centric' or, if the worker's labor is considered a resource, also to the I5.0 keyword 'sustainability'. Since the developed HAR system is subject and process-independent, a possible adaptation to lot size 1 production enables productivity despite frequent changes in the product. Combined with an adaptability to different skill levels of workers, this can be considered resilient.

In the transformation from I4.0 to I5.0, HAR methods can make an important contribution in HRC as well as in conventional manual assembly processes. The integration of the worker into the digital process twin is a prerequisite to addressing the strengths, weaknesses, and other needs of the worker in order to develop a safe, inclusive, and healthy human-centric process.

### 5.6. Automated and Adaptive Process Monitoring Systems

Assembly processes in aircraft production are predominantly characterized by manual operations. This is mainly due to the fact that aircraft assembly is defined by a multitude of time-parallel tasks in a large environment, multiple variants, and often difficult accessibility. These boundaries favor human capabilities, and therefore, value-added work is almost exclusively human-centric within aircraft assembly processes. However, this combination of human involvement within multiple, time-parallel assembly processes leads to a lack of transparency on the shopfloor and a lack of information feedback to the production control. As a result, in addition to the actual assembly processes, the employees usually also perform the task of feeding back information to the production control system, which leads to an immense expenditure of time, continuous distraction, and a growing potential for errors [73].

Automated in-progress monitoring, using an optical sensor-based solution, can help to overcome those mentioned problems and allow the employees to fully focus on their actual value-adding work while securing the continuous information flow and empowering the production control to react to deviations from the target state at an early stage [74]. The collected data can be compared with component and assembly models, process-relevant information, and deviations from the target state can be extracted. However, the implementation of an optical sensor system is a complex and time-consuming task [75], especially within the application of a large-scale assembly with its multiple parts and actors. In addition, once a system is configured, it rarely allows any adaptations to meet product or process changes. Current approaches [76] therefore model the sensor system in combination with the respective production environment, its parts, and human actions in order to simulate and optimize the sensor data beforehand. The advantages are that the sensors' viewing areas can efficiently be designed in order to cover multiple tasks, improve the quality of the collected data, and flexibly simulate any modifications based on the model before applying them to the production system.

In terms of Industry 5.0, the implementation of a sensor system, which continuously tracks the current progress, mainly contributes to the goal of human-centricity as it allows the full utilization of human skills for the actual assembly process, relieves the employees from time-consuming and recurring

FIG 9. The recorded process data can be processed and presented according to requirements and target groups.

evaluation and data transmission tasks and simultaneously reduce the susceptibility to errors. The relevant information can be derived target group-specific from the obtained data, depending on the respective application and device (Figure 9). The digital model of such a sensor system holds further potential in the context of I5.0: Simulation allows the design of the system to avoid any interference of any human action or to reduce unintentional recording of human movements. The opportunity to flexibly simulate any change of product or process and to quickly adapt the configuration of any of the sensors increases the resilience of the entire system.

### 5.7. Customizable Assistance for Manual Inspections

Similar to assembly processes, many inspection processes on aircraft components within manufacturing are also characterized by a high manual work share. Typical quality features, e.g., for aircraft cabin elements, which have to be checked manually, are geometrical characteristics like steps and gaps or surface finishes [77]. In addition to the barriers to automation, such as the size of the components or low lot sizes, the knowledge for identifying and classifying defects, e.g., for visual inspections or for carrying out processes with specific test equipment, is bound to experts. That means the employees performing the work on the shop floor cannot be easily replaced. It is therefore important to assist them in their work, not only to make the process efficient, but also to make experts feel as comfortable as possible in their work, to also counteract fluctuations of skilled employees and to keep knowledge within the company. Although there are isolated approaches in the literature for the support of processes within the production of large components, such as fault management in shipbuilding [78], inspection [79] or assembly [80] of large components, there is a lack of customizable assistance solutions motivated by the well-being of the worker.

Technologies that have been incorporated in these use cases are, e.g., mobile devices with capabilities of augmented reality features and projection systems (light [81], laser [82] or video [83]), which are able to cover large work areas. However, these solutions have in common that they are strongly driven by the process to be supported and are less oriented to the needs and preferences of the worker on the shop floor. In the context of targeted human-centeredness of Industry 5.0, it will be necessary to adapt these technologies even more to the individual to be supported. For example, this can be realized by combining several technologies or by adaptively switching individual assistance functionalities on or off based on the user's current needs. These needs can be identified, e.g., based on the current demand for assistance functions (e.g., based on vital signs, such as fatigue or alertness) or simply on personal preferences (see Fig. 10).

In summary, the strongly focused human-centeredness of Industry 5.0 and thus the related improvement of working conditions will be driven even more strongly in the future by a bottom-up approach, whereby the actual needs of people will take center stage, since many assistance technologies have already reached a satisfactory technical maturity for specific applications within the framework of Industry 4.0. An even better alignment of the available technologies with the people using it offers the opportunity to improve the working conditions of employees in the long term and to make the best possible use of their expertise and process knowledge. At the same time, proven mechanisms of assistance systems, such as the shortening of learning times and the reduction of error rates, are refined by being reflected back to its users. Within the aircraft industry characterized by a high demand of skilled employees this will indirectly contribute in a higher resilience of manual processes.

## 6. HUMAN-CENTRIC INTRALOGISTICS FOR FLEXIBLE AND RESILIENT MANUFACTURING

With up to 60% of all A320 components supplied by 12 000 suppliers [84], the aircraft manufacturing and MRO business is highly dependent on reliable supply chain and logistics processes. In the following sections, we focus on intralogistics, which deals with the organization, execution, and optimization of the flow of resources within a specific location, such as a warehouse, distribution center, or manufacturing facility [85]. Despite various Industry 4.0 efforts to automate these intralogistics processes and reduce the need for human labor, production, and MRO supply logistics are performed manually [86]. With challenges such as a variant-rich product spectrum [50], highly complex assembly scenarios [74, 76], and a wide variety of delivery points, future developments are unlikely to alleviate the need for human-based intralogistics processes. Therefore, and with additional challenges such as demographic change and labor shortages in mind, adapting intralogistics processes offers a unique opportunity to align with Industry 5.0 principles such as resilience and human-centricity. Figure 11 depicts an overview of the use cases presented in the following sections.

### 6.1. Lean and Flexible Material Supply

The delivery and supply of materials at the production site are often facilitated through means of specialized material delivery load carriers that contain the assembly-specific number of parts. Until arrival at the Point of Delivery (PoD), a lot of manual commissioning, buffering, and forwarding steps using designated hangar areas are usually required. With the available Industry 5.0 technologies, a streamlined material flow with an increased level of automation in such buffer zones, the introduction of small, modular, and moveable buffers, as well as direct delivery routing, is beneficial for achieving a more sustainable and resilient delivery chain.

Introducing automation in buffer zones will allow robotized material commissioning and packing. A large portion of the material can be handled by robots so that humans can focus on parts that require special attention and handling. An-

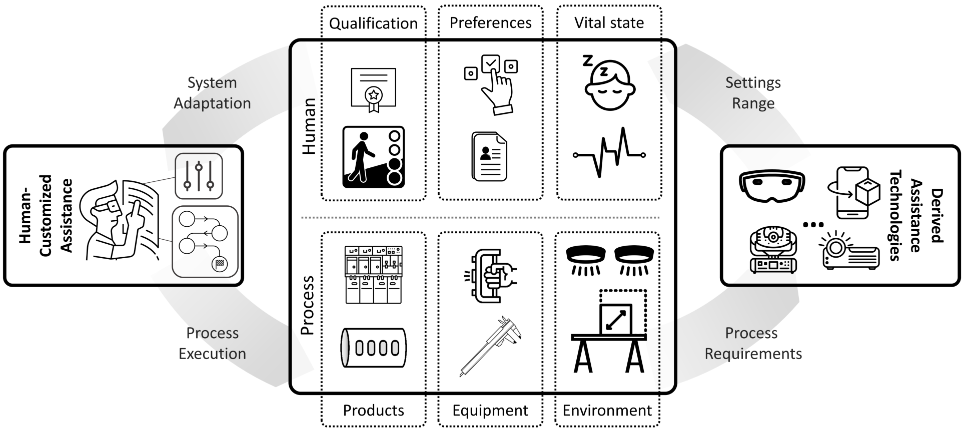

**FIG 10. Customizable assistance systems for manual inspections.**

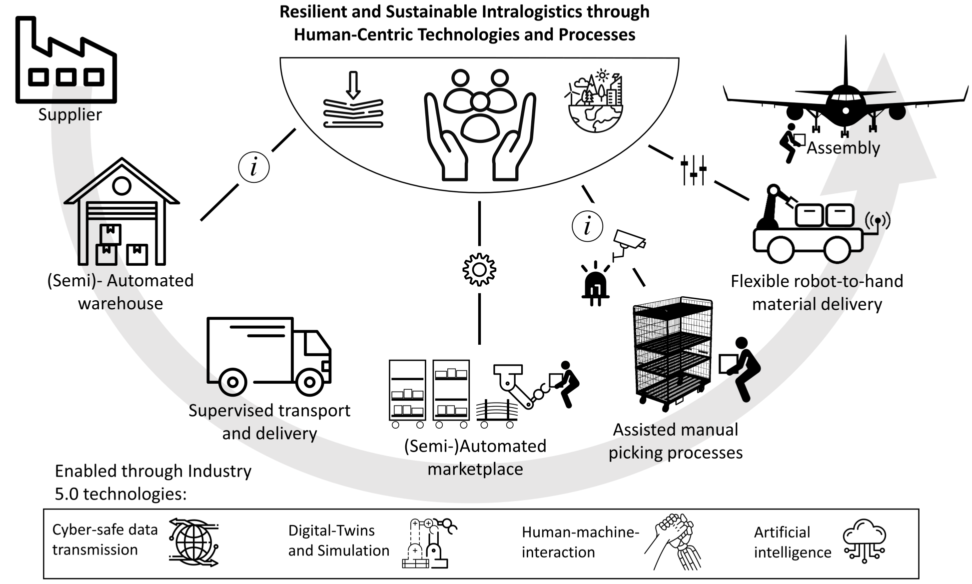

**FIG 11. Overview of use cases for human-centric intralogistics.**

other idea is the development of portable material buffers that act as Automated Storage and Retrieval (AS/RS) systems. The installation of IoT sensors along the entire delivery chain and the utilization of data-driven anomaly detection algorithms and artificial intelligence, as well as modern warehouse management systems capable of planning the next material picks, inventory placement, delivery routes, and estimating future material demand, allows to adapt to disruptions and identify alternative routes quickly.

The development and implementation of portable material buffers realized as dark storage systems outside the production facilities allows for increased sustainability due to reduced space requirements within the buildings, demands less heating and climatization, and can help to reduce transport distances and minimize commissioning and material-preparation processes. Nevertheless, a combination of IoT sensor data, a modern Warehouse Management System (WMS), and automated material handling and delivery is a step forward towards a responsive and resilient delivery chain.

## 6.2. Human-centric Material Delivery and Handover

The current delivery concept for the assembly stations relies on designated Points of Deliveries (PoDs) using shelves and boxes for small materials [86] and specialized load carriers for bigger components and pipes. The employee must pick the material needed for the next assembly step from that PoD and collect the required tools. The availability of Industry 5.0 technology allows a more human-centric approach that implements to-person delivery and material handover.

The usage of specialized cobot systems for HRC in combination with digital twins and simulations that reflect the current assembly progress can enable the delivery of tools and materials directly to the employee [87, 88]. As some of the assemblies require the technicians to work in unergonomic and uncomfortable positions, a demand-driven robot-to-hand material and tool delivery can significantly offer support and comfort. Such systems can then also support the lifting and handling of heavy materials.

With the support in especially difficult assembly positions, e.g., over-head assembly, the technician can be relieved from the material collection and handling and thus focus on tasks that require his full attention, creativity, problem-solving competency, and decision-making. Additionally, the time spent in uncomfortable positions is reduced. The introduction of HRC allows the handing over of repetitive and physically demanding tasks to the robotics systems and fosters a better partnership between humans and robots. Such a human-centric working environment can help to increase worker safety, well-being, and satisfaction. A significant challenge is developing and designing such a system, as assembly for a variant-rich product is complex and difficult to assess in its entirety. Additionally, digital twin models and simulations already introduced for Industry 4.0 need to be adapted to not only reflect the product and its environment but also focus on the workers' current actions and demands for full human-centricity.

### 6.3. Avoiding Process Disruptions Through a Smart Load Carrier

Despite the desire to become more and more productive, workers have to perform many non-value-adding tasks in the logistics process. Trends in Big Data and Industry 4.0 lead to a necessity to capture and acquire as much data from manual processes as possible. In many cases, this results in an influx of (process-disrupting) data entries that are to be performed by workers. On the other hand, components often have to be searched for in this application environment, as it is difficult to keep track of all components in chaotic environments with unstable process chains and large assembly areas. Such unnecessary activities can lead to workforce frustration; however, avoiding these is technically feasible.

Industry 4.0 technologies need to be combined with technologies associated with Industry 5.0, or they need to be rethought with human-centric values at their core. By taking familiar (technology-led) concepts, e.g., the intelligent load carrier [87, 89–91], and rethinking them in an Industry 5.0 context. There is a wealth of technologies that can be reimagined as human-centric technologies. Simple *human-machine interfaces*, such as a pick-by-light system, have the potential to connect the digital world with manual processes in a subtle and non-disruptive way. Pick-by-light systems enable individualized assistance to nudge [89, 92] the worker to the respective materials. Digitally knowing which component has to be highlighted within the correct context and towards the correct worker requires a comprehensive capture of the environment and continuous tracking of the production process. In turn, comprehensive and up-to-date *digital twins* of the process [6] have to serve as the backbone for such a system, *AI-based* visual applications may generate the necessary process updates [93, 94].

Despite the human-centered approach to this technology, human-centredness is a significant hurdle in deployment. Factors such as individual data privacy, unwillingness to be continuously tracked, mistrust of technology, and lack of confidence in their reliability - especially for AI-based systems - are challenges yet to overcome. Increasing the pure technology readiness level of such systems can be associated with Industry 4.0 aims, whereas Industry 5.0 developments should increase the *soft human-compatibility-level* with humans. Isolated technology developments cannot address these issues but have to be envisioned in a greater scope.

## 7. MAINTENANCE, REPAIR, AND OVERHAUL (MRO)

Maintenance, Repair, and Overhaul (MRO) encompasses a comprehensive set of procedures to ensure an aircraft's continued airworthiness and operational readiness throughout its life. This multifaceted field encompasses the essential tasks of maintaining, repairing, and overhauling to keep the aircraft systematically safe and dependable.

Scheduled maintenance activities ensure compliance with safety regulations and manufacturer's requirements. The activities are separated into different hierarchy levels – the so-called Checks, in which timeframes are influenced by initial operation, flight hours/cycles, number of take-offs and landings (flight cycles), and the operating area. Repair involves reacting to any identified damage or malfunctions recognized during inspections. These activities can range from minor fixes or the replacement of components to the substantial structural repairs necessitated by, e.g., bird strikes. Overhaul includes all measures to bring all components of a (sub-) system back to its initial condition. During this activity, various aircraft components, e.g., the complete cabin, are disassembled, rigorously inspected for signs of wear and tear, repaired as needed, and, if necessary, replaced to ensure the aircraft's reliability and safety. Improvement and advancements are, however, introduced during retrofit [5].

The use cases in the next sections include examples targeting Industry 5.0 ideas and concepts in composite structure repair, landing gear MRO, Non-Destructive Testing (NDT), and repairing / overhauling / repurposing cabin interiors.

### 7.1. Virtual Reality Inspection using Scanning Data

Inspection of components is an integral part of the MRO process. Aircraft parts are inspected on a regular basis following inspection schedules and guidelines defined by the aircraft manufacturer to find defects and initiate the appropriate repair. Since defects are often safety-critical, the inspection has to be detailed and thorough. Of special importance is the detection of cracks in the aircraft structure as well as many of the aircraft's components, like engine parts. Typical processes for the detection of cracks are visual inspection or manual Fluorescent Penetrant Inspection (FPI). These manual inspection processes are often times unergonomic, especially when conducted in restricted areas, provide health risks due to chemicals and UV light (FPI), or are generally tiring and repetitive. A solution to counteract these problems and humanize the process is the usage of automated inspection systems using scanning technology. One example of such a system is the automated crack detection system for combustion chambers of aircraft engines developed by Domaschke et al. [95]. The system uses robot-guided white light interferometry (WLI) to generate high-resolution 3D scans of the component surface. The resulting high-density point clouds are then automatically analyzed to find and classify cracks. However, to safely detect all cracks, the algorithms are set up sensitively, generating a significant amount of false positive test results, e.g., scratches on the component surface. In order to sort out the false positive results and meet the certification requirements, a manual review of the automated test result is needed.

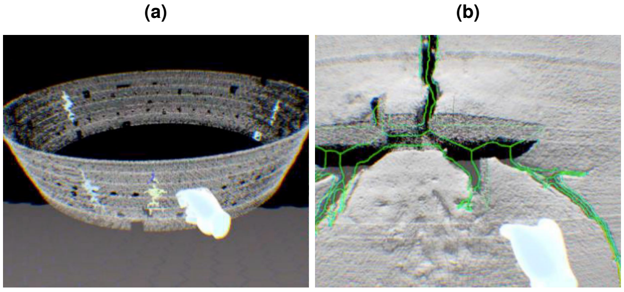

FIG 12. (a) Virtual Reality inspection of combustion chamber (b) with typical defect [55].

In order to keep the benefits regarding ergonomics, health, and safety of the automated inspection, the assessment can be conducted based on the digital representation of the part – the scan – instead of the real part. Various studies have demonstrated higher processing speeds and lower error rates for the judgment of spatial data by the use of Virtual Reality (VR) [96–98]. Therefore, a VR-based inspection system, providing an immersive virtual environment for the assessment of scanning data (Figure 12), was developed [55].

Following the concept of Industry 5.0, the system combines the strengths of humans and machines, contributing to the humanization of the inspection process and keeping the experienced staff as the final decisive and responsible authority in the process. The tracked controllers allow natural interaction with the virtual representation of the object by hand movement. The object can be intuitively positioned and scaled to the operator's needs without the physical limitations (e.g., size and weight) of the real part. The stereoscopic visualization of the data enables the perception of depth as well as improved spatial awareness compared to traditional data visualization on flat screens. Due to the detachment from the real part, the assessment can be conducted by an expert independent from his working location without the ergonomic limitations of the conventional process, contributing to the resilience and sustainability of the process by removing the need to bring the aircraft and the expert to the same location.

### 7.2. Assisted Repair of Composite Structures

During the lifecycle of an aircraft, damages to the structure occur, e.g., due to lightning strikes or tools dropped during maintenance. Additionally, aircraft structures are subjected to environmental conditions such as temperature fluctuations and cyclic loads that can result in material defects [99, 100]. While metal structures are usually repaired using doublers fastened by rivets, this method is not very appropriate for structural components made of CFRP (carbon fiber-reinforced polymers). A method better suitable for CFRP is the use of adhesively bonded scarf joints. For this, a funnel-shaped contour has to be removed from the material so that a patch made from CFRP can be bonded to the structural component. Due to the highly individual defects, the removal of the material is usually done by manual grinding, where one main challenge is to transfer the planned target geometry to the actual component. That process is very time-consuming and costly and can only be achieved by highly skilled and trained mechanics [101].

In order to facilitate the production of the scarf, reduce the time factor, and increase repeatability, a physical assistance system can aid the mechanic. One approach is a semi-automated milling system composed of an automated axis to control the infeed of a milling tool. Two further axes perpendicular to the infeed can be moved manually. The infeed axis reacts to the manual motion and controls the infeed such that a scarf is milled according to a previously specified geometry [102]. This kind of system supports the concept of I5.0 mainly in terms of human-centricity by combining the human's strengths (e.g., flexibility and the ability to react to unforeseen incidents) and the machine (e.g., high accuracy and repeatability). Moreover, it enables the update of aircraft digital twins with data on the actual scarf geometry after machining.

The use of the assistance system mainly supports human-centricity as it relieves the mechanic from time-consuming and monotonous tasks. It also carries the potential to reduce the effort for documentation by implementing automated digital documentation based on the data recorded by the machine. The knowledge of the machined geometry allows for patches to be fitted exactly to the scarf. Furthermore, the data stored in the digital twin can be used at later times within the life cycle of the aircraft, e.g., in case of another defect near the location of the previous repair or even during recycling, when it might be important to know the exact condition of the component to choose a recycling strategy, thus contributing to increased sustainability. The resilience is increased by reducing the dependence on a few specialized mechanics to produce the desired scarf geometry.

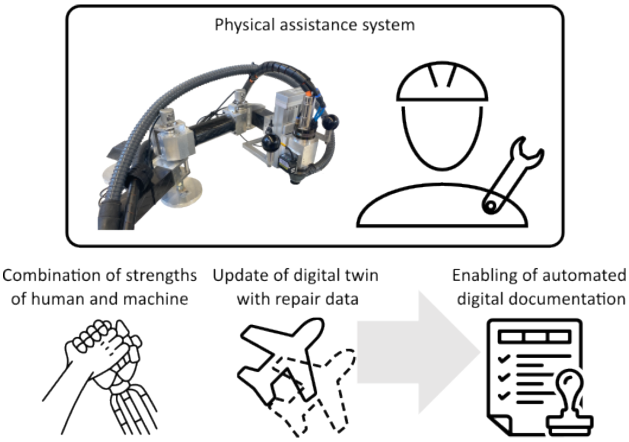

**FIG 13.** **Assistance system for repair of composite structures.**

### 7.3. Landing Gear MRO

In landing gear MRO, structural components are checked visually for any defects, such as cracks or corrosion. In case of corrosion, the defect has to be removed, and the component has to be evaluated for reuse. Assisting or automating process steps like defect inspection [56], removal [45] and evaluation [103] by means of artificial intelligence or industrial robots yield high potential in the context of industry 5.0 to increase human-centricity, sustainability, and resilience.

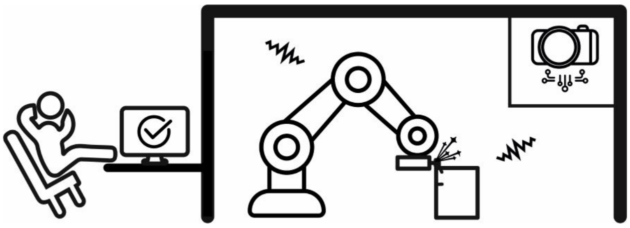

**FIG 14.** **Automated visual inspection and defect removal by grinding.**

In the case of visual inspection, imaging sensors can be utilized, especially for difficult-to-access areas. Evaluating incoming images by means of artificial intelligence may assist the worker by filtering unusual events (defects) for still-human evaluation, reducing the inspection effort for each component and reducing the timespan for human concentration/attention.

Automated defect removal by grinding with industrial robots, as depicted in Fig. 14, is a common approach to increase productivity as well as protect employees from health-endangering dust and noise. However, 100%-automation is not feasible in landing gear MRO due to a variety of geometries or random defect locations; the worker will likely still be needed in the near future for special cases.

After corrosion defect removal, the component reusability has to be determined, which is a safety-critical decision. The evaluation requires in-depth component knowledge so that some employees with their expertise have so far been considered irreplaceable, limiting overall resilience. Approaches using a decision tree and nearest neighbor algorithms may be used in the future to identify similar historic repairs to support the decision. However, the engineer will not be substituted in the near future due to regulatory reasons; therefore, these approaches are about providing a basis for decision-making.

In the context of Industry 5.0, assisting or automating the defect detection, removal, and component evaluation contributes to the goal of human-centricity and resilience by releasing the worker from tedious, time-consuming inspection and evaluation as well as health-hazardous removal tasks, counteracting the shortage of skilled workers. Also, Automated processes yield efficiency potential in terms of component reusability, avoiding spare parts made of high-grade materials, contributing to sustainable MRO. However, in addition to technical difficulties during implementations, the application of these technologies in industry faces regulatory hurdles, e.g., with regard to the reliability of the technologies or liability.

### 7.4. Re-pair/-furbish/-manufacture of Aircraft Interior Components

Throughout a commercial aircraft's operational lifespan, cabins are modified several times to adapt to evolving customers' and airlines' requirements and needs. These adjustments are primarily motivated by enhancing passenger satisfaction but also increasing the airline's revenue through introducing, e.g., additional seat rows [104, 105]. Complete recycling of the cabin interior is only partially possible, as highly processed composite materials are often used here. Focusing on the concept of the circular economy, the topics of reusing, repairing, refurbishing, and remanufacturing move into the foreground.

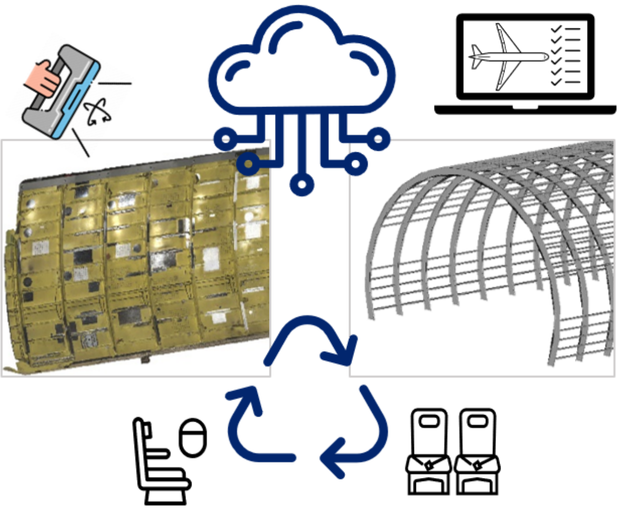

**FIG 15. Assessing repair/-furbishment and -manufacture potentials of cabin components based on an Digital Twin.**

When deciding which of these processes suits a particular cabin component, the as-designed documentation of the components is required on the one hand, and an as-is state assessment, e.g., for visual defects, on the other. Already proposed technologies, e.g., 3D scanning [104] and Augmented Reality (AR) systems [106], enable operators to gather such an as-is state inside the cabin. Alternatively, the assessment can take place post-disassembling. A value-adding technology here can be a system to automate assessing the component-individual as-is state, e.g., image and AI-based anomaly detection, such that for each major modification, as-is state assessment is an integral part of planning the cabin overhaul.

The idea of digital imaging and managing the as-is state based on as-designed and newly acquired data is subject to current (industry) research efforts in recent years. Previously described aims are not only increasing the planning reliability but also automation of planning tasks, everything under the overarching concept of implementing a Digital Twin (DT) that replicates the real physical object instance following the Industrie 4.0 directive [104, 105, 107]. However, in the context of Industrie 5.0, the asset's Digital Twin can additionally serve as an automated assessment of cabin components' repair, refurbishment, or remanufacturing potentials. The industry can contribute here by implementing circular economy practices based on exploiting information and data from the digital to physical instance.

## 8. CORE VALUES, TECHNOLOGIES, AND CHALLENGES

The use cases given in the previous sections target different facets of Industry 5.0‘s core values. Summarizing these, as depicted in Figure 16, with an effort to outline intersections, all three values, human-centric, resilient, and sustainable, are targeted with different extents and superimposition.

The use cases from manufacturing (s. Sections 5.2 and 5.4-5.7) mainly contribute to the overlap between increasing a system‘s resilience and setting the human into the center of the process. Flexible, adaptable human-based production systems, as shown in the use cases, are currently subject to research. Besides technology, e.g., Augmented Reality (AR), serving to assist a human, accelerating the ramp-up of a process in the context of introducing novel technologies, e.g., inspection processes for new H2 systems, is a promising direction and targets sustainable values (s. Section 5.3). Lastly, as already discussed, Additive Manufacturing (AM) reinforced with carbon fibers can be the basis for flexible, customized, bio-inspired parts, contributing on the one hand to saving fuels by reducing an aircraft's weight but also to manufacturing parts demand-based, saving grounding times and environmentally costly worldwide shipping of parts. It is not unusual for an aircraft to be grounded for a few days, waiting on parts manufactured on the other side of the world. So AM can provide resilient and sustainable values in the context of aircraft design, manufacturing, and repair.

The examples of implementing Industry 5.0 ideas in the context of valuing up intralogistic processes in the aircraft production and MRO domain are either increasing resilience through lean processes (s. Section 6.1) or facilitating human work through smart, connected, and uniform technologies, so serving the idea of placing the human's wellbeing back into the center (s. Sections 6.2-6.3).

Two of the use cases from MRO processes target the objective of minimizing repair demands (s. Sections 7.2-7.3). Here, a human-assisted system allows for minimal invasive repairs since the expert knowledge can be fully utilized. On the one hand, one can argue that, thereby, the human is given back value by not fully replacing him; on the other hand, joining the universal, generalizable skills of a human and machinery strength, perseverance, and objectivity,

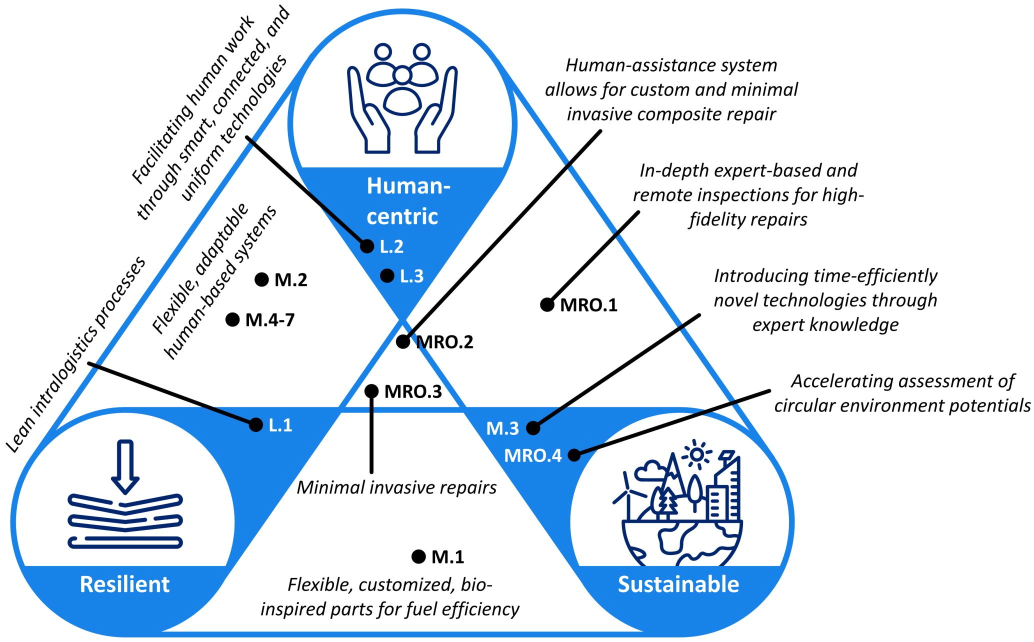

**FIG 16. This works' use cases and the related Industrie 5.0 core values.**

the resilience of the repair process / system is definitely increased. Moreover, concurrent digitization or, at first, digitizing the object under test allows for remote assessments, meaning experts do not have to travel around the world to the specific part or aircraft. On the one hand, this reduces the environmental travel expenses; on the other hand, it reduces the stress and strain of during a time-important travel on the operator (s. Section 7.1). Finally, the last use case targets accelerating circular economy practices in the aircraft industry by utilizing the idea of an always up-to-date Digital Twin (DT) to accelerate the assessment of repairing, refurbishing, and remanufacturing aircraft interiors. Making such quantities more easily available resources for this purpose will undoubtedly lower the threshold to incorporate a circular practice on the business side as well.

In the following section, we will discuss the challenges of enabling technologies in implementing Industry 5.0 ideas and concepts in the aircraft production and MRO industry context.

## 8.1. Enabling Technologies in Aircraft Production

Working towards the Industry 5.0 core values of human-centricity, sustainability, and resilience, different already existing and future technologies enable applications. As we already use case-driven outlined in this work, multiple technologies already exist, but multiple ones are only proven and evaluated at a low Technology Readiness Level (TRL). The next subsections will discuss individual enabling technologies in the aircraft production domain following the taxonomy from a workshop with European industrial leaders (s. Section 3.2).

### 8.1.1. Individualised Human-machine interaction

The value of human-centric production is driven by the need to place the human into the core, into the center of a process. Therefore, feeding input to and gathering output from the human operator must be technologically enabled. Additionally, focusing on the individual needs and skills of the operator, these technologies must be able to (re)act individualized. Aspects like multi-lingual speech and gesture recognition capture a human's current action or state (s. Section 5.5) and are on TRL 5-6, but as shown in the use case, not currently implemented in current industries. Also, tracking technologies to assess the physical strain and stress of employees automatically are subject to research.

On the other hand, the cognitive relief of an employee through an assistance system, as shown in the use case depicted in Section 5.7, is actively pursued in the industry. Also, augmented, virtual, or mixed-reality systems play a particular role since they, individually, directly enable input and output to the human operator (s. Sections 5.2-5.3). However, the shift in paradigms during the progression from Industry 4.0 to 5.0, namely the evolution from an efficiency-oriented digitization to a more considerate utilization of available resources, poses various challenges to the employment of AR within industrial applications. The shift holds the potential to facilitate the integration of a more diverse workforce into industrial settings. However, it overall demands an increased level of customization of AR applications, thus emphasizing the necessity of extended research within the domain of long-term AR-assisted industrial human-machine interaction.

The complementary to cognitive assistance is physical assistance through mechanical actuators, e.g., in the form of collaborative robots, online teachable, so adaptable to new processes or individualized operators' needs. Instead of teaching a cobot, a subsequent intersection is physically enhancing the human operator. The technology is basically already proven in operational industrial systems, but the flexible and lean integration into existing processes requires further research and development, as shown in 5.4.

### 8.1.2. Bio-inspired Technologies and Smart Materials

Bio-inspired technologies in aviation are driven by operational benefits, foremost reduction of fuel consumption, and thus heavily contribute to general sustainable aviation. Examples are bionic-inspired frames and stringers that can be produced through 3D printing [108]. Although recent advantages made 3D printing for metallic components both economically feasible and aviation safety compliable, increasing the technology readiness level for composite structure 3D printing (see Section 5.1) can further benefit this goal. However, the effects of such sustainability contributions can only take place for newly produced aircraft. Due to the long life cycle and the high value of existing aircraft, this is a low-paced contribution to a sustainable aviation industry.

In the meantime, e.g., the bio-inspired *AeroShark* [109] technology that is retrofitted on planes offers a significant decrease in fossil fuel burn for the current fleet. Nevertheless, even such technology is subjected to aircraft production and maintenance characteristics as it requires sufficiently extensive facilities to perform this unique and unusual type of retrofit. Due to the novelty of this technology, no automated application procedures are available, leading to further manual processes that the various above-discussed technologies can aid.

### 8.1.3. Digital Twins, Simulation, Data Transmission, and Storage

Digital Twins (DT) digitally replicate a physical asset, instance-wise, to enable applications such as, e.g. simulations. So the idea is to, e.g. firstly, virtual test and simulate modification of an existing system before introducing changes into the real world. Implementing a holistic digital twin of a complete aircraft or an aircraft final assembly line is ideal theoretic since products and processes are, on the one hand, often not digitally modeled; on the other hand, they require many different types and dynamic multi-scale models and overarching interconnection and utilization in a simulation is not feasible. Also, focusing on incorporating the human part, the concept of a Human Digital Twin (HDT) is still subject to research. For example, to enable human-centric intralogistics, already existing DTs and simulations need to be extended to include the workers' current activities, then forming an HDT to infer their demands and, e.g., enable robot-to-hand material delivery. For such, further research in Human-Robot-Collaboration is required on how to hand over material in flexible assembly processes.

Closely related to DTs are aspects like data transmission, storage, and analysis technologies, which are particularly complex, facing massive amounts of data. Instead of dealing with a holistic digitally enabling system, purpose-bound and domain-specific data and information can be used for replicating (sub-)systems [6]. This basis may then serve as the enabling technology for further applications fulfilling the core values of human centricity, working, and operational safety.

### 8.1.4. Artificial Intelligence

Future advances in Artificial Intelligence (AI) have the potential to benefit many aspects of aviation. Excluding applications such as optimized flight path routing and passenger guidance, the above use cases consider AI as a tool to support future production aspects — interactive and autonomous responses of robots and assistance systems, especially in logistics (s. Section 6). Matching and combining human expert knowledge with AI-based experts has significant application potential in all inspection and defect analysis aspects, e.g., as shown in Section 7.1. The multifaceted nature of defects, combined with additional contextual aspects such as the expected lifetime or historical failure history of the component, results in a complex problem that cannot be solved by either a human or a technological system alone. The latter is necessary to navigate the high dimensionality of the problem, and the former to enable customer confidence and traceability throughout the inspection process. Additionally, AI-based systems have the potential to utilize the formalized knowledge of production and product digital twins, as discussed above. Only when working on such a knowledge base is an AI capable of optimizing entire process chains.

## 9. DISCUSSION AND OUTLOOK

Since the beginning of this century, industries have faced various societal and environmental challenges, in which the COVID-19 pandemic-related shutdowns shaped the latest most significant interruption. Besides multiple other actions, a governmental, EU-backed response here in forming and standardizing a novel terminology, a successor of I4.0 – the I5.0 values of human-centric, sustainable, and resilient – tries to place values to the subject of industries in an effort to change directions for campaigns, funding, research, and development. Previous lived objective to increase productivity does not win future markets, primarily caused by human-related challenges such as demographic change and if industries must fully stand for their products‘ current and future pollutions. Aiming at finding a common term therefor, we introduced *Consideration* as the overarching I5.0 depiction (s. Figure 2). I5.0 ponders the various societal, environmental, and deductivating industrial needs. Besides the EU-given definitions, we encourage current research to work on an I5.0 reference architecture / framework to, on the one hand, be able to name, measure, and classify I5.0 added values in a standardized manner but also are guided in the three values directions.

Strictly speaking, current companies in the aircraft production and MRO market do not use the I5.0 terminologies but are already working on various aspects of reshaping from technology-driven to value-driven concepts without explicitly stating. As we outlined in the various use cases from current, ongoing, and not yet realized research and development projects, overall, the aircraft industry grapples with the complex demands of I5.0 as a whole, but previous subjects to research and development on technologies already partially fulfill I5.0 core values in different aspects, but often require a reframing or rethinking in utilizing these. All Industrial revolutions were enabled by novel technologies, as is I5.0, but the utilization of these can be different compared to I4.0.

In 2011, Europe's Flightpath 2050 already introduced the terming of serving society's needs in addition to maintaining global leadership [110], so it already targeted one I5.0 core value of protecting the environment and resulted in, e.g., Airbus's current H2-based aviation research and development efforts. Here, research is necessary on the finer to the larger scale. On the one hand, developing existing approaches and technologies further is of interest, as outlined in the use cases, especially in the intralogistics, repair, and overhaul markets. Aircraft fleets are not replaced from day to day, so overhauling and retrofitting existing (sub-)systems must be forced, targeting sustainable values. Here, human-centric and resilient values follow this core objective. On the other hand, disruptive changes in the product aircraft require flexible, adaptable production systems that are capable of introducing novel technologies into the market in a timely manner – ramp-ups must be shortened. A lot of bright minds will shape future technologies, which the I5.0 idea encourages to focus first-handed on the three core values instead of only increasing production efficiency neglecting the challenges of this century.

Concluding, the unique nature of aircraft production and MRO, as well as the environmental impact associated with the products themselves, allows for a significant potential to prioritize human well-being, reduce environmental impact, and fortify the industry against disruptions in this era. In the context of mostly already missed I4.0 targets and according to the motto „now more than ever," the aircraft industry, in particular, is now responsible for tackling the challenges of the current era and thus taking a major step in the direction of I5.0, enforcing and working on multiple enabling technologies from the I4.0 to the I5.0 context, through, as already conducted in multiple facets, redirecting research funds but also company-financed developments.

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