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ORIGINAL PAPER

Industry 5.0 in aircraft production and MRO: 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 (I4.0), 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 digitalizing significant parts of their value- and non-value-adding activities. However, in the face of current social and environmental challenges, future industries will need to shift from purely technology-driven to value-driven, working sustainably with resources, including human capital. Together, these approaches constitute the idea of Industry 5.0 (I5.0). On the one hand, the aviation industry faces the challenge that even I4.0 concepts and technologies are not yet fully exploited or implemented. On the other hand, due to the specific characteristics of aircraft production and MRO as well as the environmental impact of the product, a tremendous potential arises regarding placing human well-being back into the center of adding value and decreasing environmental footprint while building an industry that is resilient and fortified against disruptions of this era. In line with the I5.0 terminology, in this work, we outline the challenges and opportunities of integrating I5.0 principles into the aircraft production and MRO industries, focusing specifically on the scope of selected use cases.

Keywords Industry 5.0 · Aircraft Production & Manufacturing & Logistics · MRO · Human-centric · Sustainable · Resilient

Abbreviations

AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
CFRP	Carbon Fiber-Reinforced Polymer
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
DT	Digital Twin
EASA	European Union Aviation Safety Agency
EC	European Commission
FDM	Fused Deposition Modeling
FPI	Fluorescent Penetrant Inspection
GIM	Green Intelligent Manufacturing
HAR	Human Action Recognition
HCPS	Human-Cyber-Physical System
HDT	Human Digital Twin
HRC	Human–Robot Collaboration
I1.0–5.0	Industry 1.0–5.0
IoT&S	Internet of Things and Services
MRO	Maintenance, Repair, and Overhaul
NDT	Nondestructive Testing
OEE	Overall Equipment Effectiveness
PLC	Programmable Logic Controller
PoD	Point of Delivery
QA	Quality Assurance
TRL	Technology Readiness Level
VR	Virtual Reality
WLI	White Light Interferometry
WMS	Warehouse Management System

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1 Introduction

The 4th industrial revolution was defined by the need to globally interconnect machines, processes, and resources, increasing productivity and, thus, prosperity. Ten years after

Fig. 1 Core values of I5.0 [4]

the term "Industry 4.0" became more widely used, having been introduced at the Hannover Messe 2011 [1], the European Commission (EC) proclaimed "Industry 5.0" in an effort to force current industries to reposition their roles in society and explicitly consider current global environmental challenges [2]. While I4.0 is technology-driven, the I5.0 is value-driven. It is supposed to be a technology transformation with a particular purpose.

Up to now, authors, administrative 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 (see Fig. 1) [3], incorporating the idea that industries must become more value-driven in addition to technology-driven, working sustainably with resources, including materials and human capital, respecting the world's resource limits, as well as considering societal objectives beyond jobs and economic growth.

The aircraft production[1] and MRO market shared by design, manufacturing, and maintenance organizations, according to EASA 21 J/G and 145 [5], is mainly dominated by numerous manual, non-digitized processes resulting in low levels of automation [6]. Despite the technologies and advantages that were developed in the last ten years as a result of I4.0, the introduction of these into the aircraft production industry remains incomplete. The main challenge that inhibits the implementation of service-oriented 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 within a fixed position assembly. 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 given 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, longevity 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. Likewise, as seen during the COVID-19 pandemic, the aircraft industry is particularly vulnerable to non-influenceable disturbances [13]. Given these unique challenges and characteristics, the aircraft industry is especially suited for bypassing the full implementation of I4.0 and instead directly focusing on incorporating I5.0 ideas. The shift towards I5.0 allows the industry to address its specific needs more effectively, such as sustainability and resilience, by adopting a value-driven approach rather than pursuing pure automation. Instead of forcing a path toward complete automation, the industry can embrace the transformative adaptation that I5.0 concepts and ideas offer. Future technology 'decision-makers' in the aviation sector will play a crucial role in shaping the 5th industrial revolution here, where the focus will shift from merely globally interconnected and automated processes to integrating intelligent systems that enhance human capabilities and ensure sustainable and resilient operations. By directly adopting I5.0 ideas and concepts, the sector can, therefore, align with broader societal and environmental goals.

In line with the terminology and ideas behind I5.0, we present several use cases in which we outline and elaborate on the core characteristics, challenges, opportunities, and enabling technologies/concepts for sustainable, resilient, and human-centered activities in the different lifecycle phases of an aircraft. While I5.0 has garnered significant attention in broader industrial contexts, there is limited exploration within the aircraft production and MRO sectors. Much of the existing literature focuses on I4.0, emphasizing technological advancements without sufficiently addressing the shifts I5.0 represents. The integration of these principles, especially in this complex, highly regulated industry,

[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.

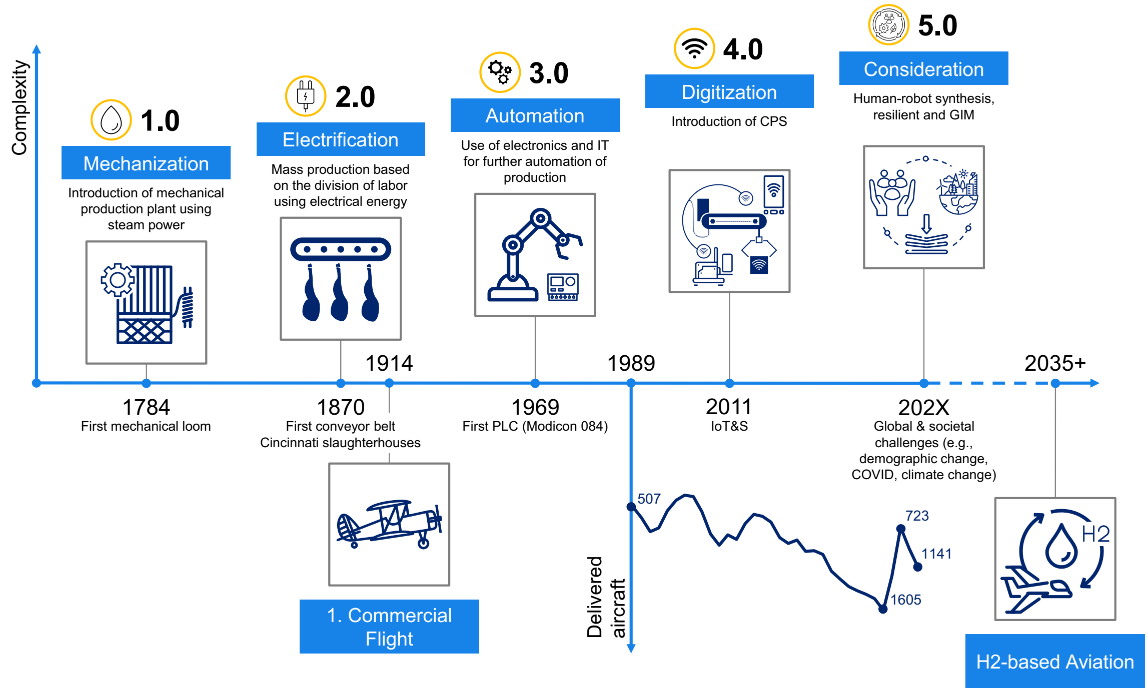

Fig. 2 Timeline with milestones from I1.0 to I5.0, first commercial flight, combined Airbus and Boeing commercial aircraft deliveries, and Airbus' H_2-based aviation goal (based on [2, 16–19])

presents unique challenges that have not previously been discussed. We seek to contribute here by providing a concrete, case-driven analysis of how I5.0 principles can be applied across different lifecycle phases of an aircraft - from manufacturing to maintenance.

The rest of this work is structured as follows: First, we revisit the industrial revolutions in Sect. 2, including the common I5.0 definition, characteristics, and enabling technologies in an industry-neutral way. In Sect. 3, we describe how the aircraft industry lived through the previous industrial revolutions and analyze what motivates the need for I5.0. In Sect. 4, we describe our analysis approach, including how we structured the use cases in this work. We continue with Sects. 5, 6, and 7, in which we elaborate on use cases from manufacturing, intralogistics, and MRO, respectively. Subsequently, in Sect. 8, we summarize, discuss, and conclude the results and findings of this work.

2 Industrial revolutions

2.1 Industry 1.0 to 4.0

The 1st Industrial Revolution (I1.0) saw the rise of mechanical working machines powered by water or steam, with the mechanical loom, developed by Edmund Cartwright in 1784, marking the beginning of mechanization [14] (see Fig. 2 for the industrial revolutions timeline). This era drastically improved productivity, aiding in the provision of clothing and food. The 2nd Industrial Revolution (I2.0) introduced mass production through electrically driven assembly lines, beginning with the first conveyor belt in Cincinnati's slaughterhouses around 1870. This concept was further developed by Henry Ford for large-scale industrial production. The 3rd Industrial Revolution (I3.0) in the 1960s brought automation, enabled by Programmable Logic Controllers (PLC) like the *Modicon 084*, allowing for streamlined processes and mass production of product variants. This shift turned the market from a seller's to a buyer's market, with increasing emphasis on quality and uniqueness [15].

In contrast to the 1st to 3rd industrial revolutions, the subsequent 4th and 5th were deliberately initiated, which makes the term "revolution" debatable. The underlying idea is that the evolution of technologies and processes is not merely observed but intentionally driven by strategic initiatives, industry leaders, policymakers, and researchers.

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 (IoT&S) [20]. [21] discusses the key concepts of I4.0, which can be summarized as follows:

- Service-oriented reference architecture;
- Intelligent, self-organizing CPPS;

- Interoperability between CPPS and humans;
- Adaptability and flexibility to changing requirements;
- Optimization for Overall Equipment Effectiveness (OEE);
- Data integration across disciplines and entire lifecycle;
- Reliable and secured communications between businesses;
- Data security.

2.2 I5.0

The term "Industry 5.0" - in short, integrating societal goals and sustainable practices into the producing industries - emerged in response to the current challenges of societies and industries. I4.0 is characterized by technology-driven advancements, such as the Digital Twin (DT) concept and Artificial Intelligence (AI), aiming at enhancing production efficiency and flexibility. In contrast, I5.0 complements these technological advancements but focuses on value-driven principles [22], e.g., principles of social justice and sustainability [23]. By 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 that account for and respond to contemporary challenges. Essentially, it tries to answer how industry and the latest social and environmental trends and requirements can or must co-exist in harmony [24]. On the tenth anniversary of I4.0, in 2021, this idea was taken up by the EC (see Fig. 2), who recognized the importance of repositioning the roles of European industries in society and environment and so determined to advocate new ideas in research and development to strengthen the industrial landscape [4].

2.2.1 Fundamental blocks

Before the EC officially defined what I5.0 entails, a number of definitions were proposed in the literature [22], all of which focused on different characteristics, including the human-centric or human-robot co-working part [25–27], novel technology [28], or outlining that the interweaving of both is necessary. In such an approach, intelligent devices, systems, and automation co-operate with human intelligence and their knowledge [15]. In summary, 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 (see Fig. 1).

Human-centric

Previous industrial revolutions were fundamentally driven by the notion of separating machines from humans (see Fig. 2), which resulted in advanced robotics even converging into humanoid robotics— in an effort to try to mimic human behavior. In contrast, I5.0 places human skills and intelligence back at the center, proposing that humans and machines best work together [27]. The 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 DTs 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 individual human needs and interests through machines, placing the operator's welfare at the center [33]. 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].

Resilient

Crises and technological advances in this century have shown 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, I5.0 must be *agile and resilient* based on flexible and adaptable technologies [4]. I4.0 focused on long, globalized, connected value and supply chains, as well as cost-effectiveness and efficiency, but these foundations have been shaken during instances of geopolitical realignments and calamities, e.g., the COVID-19 pandemic. It underlined the vulnerability of our existing paradigm of globally interconnected production, which is particularly crucial in instances where value chains are instrumental in meeting fundamental human necessities, e.g., healthcare and security. Rethinking rigid and inflexible supply chains as well as prevailing work methods and strategies is necessary but without de-globalizing the industries.

Sustainable

The natural limits of the planet Earth are exceeded year after year; industries must respond here and embrace sustainability [3]. I5.0 leads to action on *sustainability and respecting planetary boundaries* [4]. This entails establishing circular procedures summarized under the nine *Rs* [34]: 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 [35]. In this context, [36] introduce Green Intelligent Manufacturing (GIM)—a transitional paradigm that describes the necessity of merging intelligent and green technologies; in short, intelligent techniques enable green/sustainable objectives.

2.2.2 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** that mimic natural systems to improve functionality and efficiency, including, e.g., bio-intelligent manufacturing [37], and **smart materials**, materials with embedded sensors and enhanced features while being recyclable;
3. **Real time-based DTs and simulation** to model entire systems;
4. **Cyber-secure data transmission, storage, and analysis technologies** that are capable of secure data handling and system interoperability;
5. **AI**, e.g., to detect causalities in complex, dynamic systems, leading to actionable intelligence;
6. **Technologies for energy efficiency and trustworthy autonomy**, as the technologies named earlier will require large amounts of energy while demanding autonomy to increase resilience.

These fields do not exist independently, nor do they contradict each other. Facing the complexity of I5.0 challenges, they are to be connected and overlaid with each other. We will use this taxonomy in the following of this work.

3 Aircraft industry

The lifecycle of an aircraft includes distinct phases: development, production, MRO, retrofit, remanufacturing, and end-of-life activities. Each of these phases shapes characteristics that make the industry distinct from other industries, e.g., automotive. As outlined in previous work, the aircraft production and MRO industry can be characterized by (see [6] for a extensive elaboration):

1. High proportion of manual processes;
2. Dependence on expert knowledge (e.g., classifying defects);
3. R-Processes, like, remanufacture, reuse and retrofit systems, subsystems, and components;
4. Fixed position final assembly;
5. Historically grown processes;
6. Distributed production with a large number of suppliers;
7. High levels of inspection, testing, occupational health and safety, certification, and documentation.

These distinct characteristics influenced how the industry passed through the industrial revolutions up to I4.0 and also affect how I5.0 principles shape the industry. In the following sections, we first review the industry regarding the industrial revolutions up to I4.0 and then specifically motivate I5.0.

3.1 Industries 1.0 to 4.0

Since the first commercial flight in 1914 (see Fig. 2), different product innovations have been established on different system levels, such as digital fly-by-wire technology or carbon fiber fuselages. However, disruptions, e.g., highly automated production lines, as in the automotive industry, have not been implemented in aircraft production [38]. Thus, the base product and the general boundary conditions remained. Therefore, no typical line-type mass production, as established in I2.0, and only a low level of automation (I3.0) was introduced. In recent years, long after the automobile or consumer electronics production, efforts were made to introduce automation in processes such as carbon fiber prepreg layup [39], cabin interior production [40], and the fuselage assembly [41]. At the same time, I4.0 approaches began to make inroads into aircraft production. These mainly include digitalization, 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 [42, 43], information security measures in IIoT-based manufacturing [44], HRC in assembly [45], Augmented Reality (AR) in maintenance [46], and AI in inspection tasks [47], as will be elaborated in specific use cases in Sects. 5 to 7.

3.2 Motivation for I5.0

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 halved in 2020 (see Fig. 2). The world passenger volume has recovered year by year since then, but the aircraft delivery still has not recovered 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 impact of aviation on the climate, ambitious but necessary goals in fossil fuel emissions reduction were set, which paved the way towards an actual disruption: the development of a hydrogen-powered passenger aircraft [48] (see Fig. 2). This bears the opportunity to co-design products and production for the first time to allow for the expedient introduction of I3.0, I4.0, but also I5.0 measures in aircraft production. Thus, not only the aircraft itself but also its production can and must become more sustainable, resilient, and human-centric.

4 Analysis approach

This paper adopts a case-driven research approach to explore the integration of I5.0 concepts / ideas into the aircraft production and MRO industries. We focus on identifying enabling key technologies, challenges, and opportunities, aiming to provide a view of how I5.0 principles can be applied. The use cases presented in this study are derived from the authors' ongoing and past research projects as well as interviews with experts within the field. While we do not aim to cover all possible scenarios with the selected use cases, our objective in this publication is to advance research on I5.0 applications in this domain through the given use cases.

Based on the use cases, we identify gaps and propose potential solutions, practices, and ideas that address these gaps in the scope of I5.0 practice in the aircraft production and MRO industry. Each of the use cases in the Sects. 5, 6, and 7 is structured into three parts:

1. A **summary of the use case**, outlining the context, objectives, and the specific challenges it addresses within the aircraft production or MRO processes;
2. Exploring **how I5.0 technologies / ideas / principles can be implemented** within the use case. We refer to enabling technologies as outlined in Sect. 2.2.2 and stick to the same naming convention, although the terms span categories, which describe a set of particular technology bricks. We put these in italics;
3. Discussion of the specific **challenges and opportunities** associated with the use case, particularly in relation to I5.0's three key objectives: human-centricity, sustainability, and resilience.

After the presentation of the use cases, we consolidate and summarize in Sect. 8.1, which constitutes a synthesis of the insights gained from the use cases. In Sect. 8.2, we specifically outline the enabling technologies that are most relevant, providing a clear guide for industry stakeholders or researchers looking for implementation insights into I5.0 principles in the aircraft production and MRO sector. The presented approach ensures that the results are grounded in both theoretical knowledge, as presented in Sects. 2.2 and 3, and practical applications, as we present in the subsequent use cases. This dual focus enhances relevance and ensures actionability and applicability in real-world settings.

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 [49], saving up to 17% fuel [50]. 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 [51]. The airframe structure assembly has different levels, starting with fuselage section parts and ending in marrying the overall fuselage ton and wings [52]. 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 the OEM's production facilities. The final assembly is mostly done manually, where most of the value-adding activities are conducted inside the aircraft. Pre-assembly is difficult based on the dimensions, narrow accesses, and individual configurations. Following the assembly tasks, inspection for Quality Assurance (QA) is an integral and highly important activity since the aircraft has critical safety characteristics.

The activities involved in aircraft manufacturing, whether conducted by humans or assisted by machines, are particularly relevant to the concepts and ideas of I5.0. This is reflected in the seven individual use cases presented in the following sections.

5.1 Smart materials and bio-inspired technologies through 3D printing

Carbon fiber composites have long represented a promising material for aircraft production due to their low weight and high stiffness and strength [53]. 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 [53]. This common production method also makes it hard to facilitate the anisotropic property of the composite material fully [54]. 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 [54].

By being able to inlay copper wires or even use the carbon fibers themselves as conducting material, this manufacturing method can be used for the production of *smart materials*. Furthermore, the structural optimization process oftentimes results in *bio-inspired geometries*. This multidimensional 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 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 [55, 56]. Carbon fibers are also able to be recycled [57], making this process an important realization of I5.0 manufacturing principles.

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 by promoting localized manufacturing, which results 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.

Fig. 3 AR-assisted robot programming in aircraft fuselage manufacturing

5.2 Skill-independent 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 AR-assisted robot programming (see Fig. 3). 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 [58].

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. Here, AR serves as a *technology for human–machine interaction* to combine the strengths of both.

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. For developers and users, it is required to comprehend how various types of AR technologies, especially in the areas of visualization, interaction, and tracking, can be efficiently combined and presented to a diverse user group.

5.3 AR-assisted H_2 leakage inspection

Hydrogen is expected to 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 and dimensions of aircraft components, along with the unstable behavior of leakage gas flows, necessitate manual measurements, as automation remains technologically complex, inflexible, and cost-intensive. A possible use case could be the inspection of hydrogen-carrying pipe systems between the hydrogen tank and the fuel cell during ground checks, as shown in the upper part of Fig. 4. All components undergo a standardized testing procedure, which includes a pressure drop test, a soap bubble test, and, finally, the use of sniffing devices. However, manual leakage testing with sniffers is time-consuming and strongly dependent on the expertise of individual technicians. Electrochemical sniffer devices measure the hydrogen concentration only at specific points on the sensor and can be equipped with suction devices. The manual process control is complex because the sensor can only detect the invisible gases with a delay, resulting from both the sensor principle and the duration of gas transport from the intake to the sensor surface [59].

The integration of AR systems, a *human–machine interaction technology*, can assist humans in the inspection process by providing additional digital information and complementing employees' flexibility and individual expertise. AR glasses overlay real machine parts and measuring equipment with 3D animations and metaphoric visualizations to enhance sensor guidance during the inspection process, allowing for full utilization of both hands. This results in a more efficient and standardized inspection process, improving safety and data acquisition quality. For the given use case, the lower part of Fig. 4 shows how an AR application can assist users by locating the correct components to measure from a digital inspection plan, replacing traditional paper-based documentation. During the inspection, optimal sensor trajectories are visually presented (e.g., using a ring

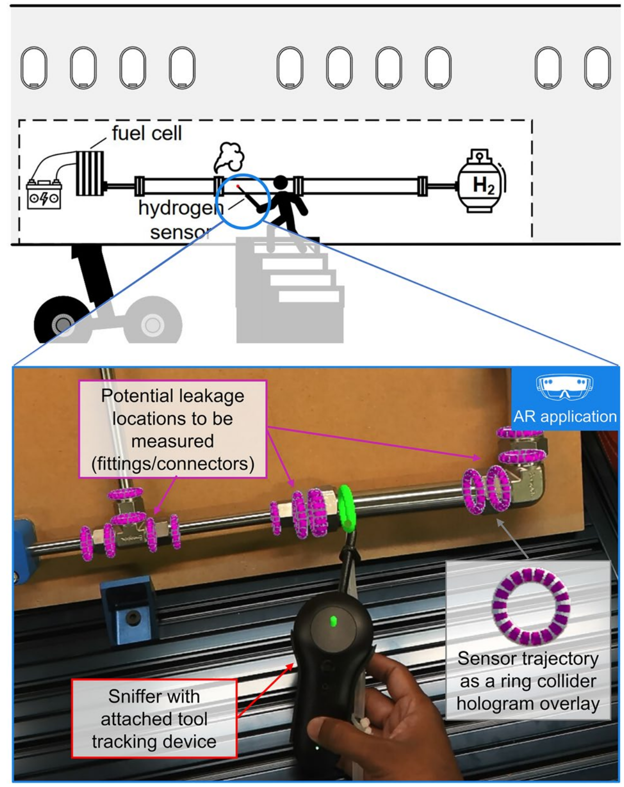

Fig. 4 Top: Use case of an AR-assisted H_2 leakage inspection on aircraft components; Bottom: AR application for measuring the leakage of fittings in a pipe system with a sniffing sensor

collider for circular motion) while ensuring correct sensor positioning and velocity for the specific sniffing sensor with real time tool tracking devices attached. These trajectories are derived from system component data and are dynamically adjusted based on real-time tracking. When a measurement trajectory has been successfully completed, the ring collider is colored green. Additionally, the sensor signals are analyzed, processed, and visualized in real-time, effectively making the otherwise invisible gas visible through holograms. Further data analysis and visual user feedback support precise leak localization. The integration of a digital database enables comprehensive documentation of the measurement process, ensuring traceability and compliance with quality standards. AR-assisted inspections not only improve hydrogen leakage detection but also enhance the overall quality and efficiency of various other inspection tasks. By merging digital tools with human expertise, such a system can significantly reduce errors, improve safety, and adapt to changing procedures. This approach places the worker's expertise at the center of the process while reducing cognitive load.

The rapid emergence of new hydrogen systems and aircraft variants-such as fuel cells and H_2 combustion turbines-increases the need for flexible AR applications tailored to

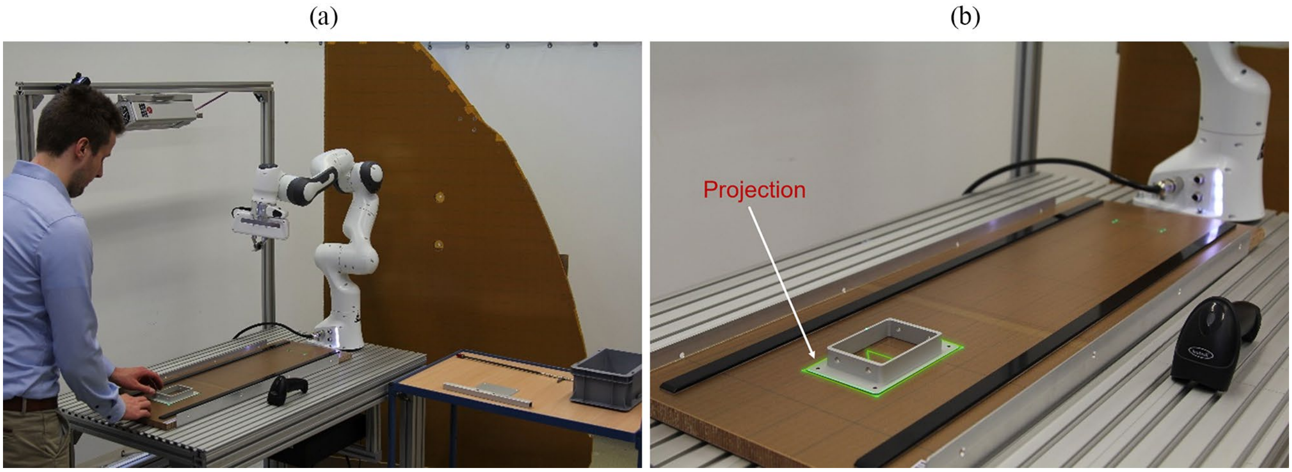

Fig. 5 **a** Flexible assembly station for aircraft interior assembly including a cobot and a laser projector; **b** Visual assistance by projecting a component's position (based on [45])

each design. Application development requires adapting AR hardware, tracking methods, UX guidelines, and communication interfaces. To meet this demand, authoring systems must enable leak inspection applications to be configured with digital models, metadata, and domain knowledge while requiring minimal specialized expertise [60]. In particular, these authoring systems must provide the definition of optimal sensor trajectories for leak inspections. In aerospace, detailed 3D CAD models of aircraft and hydrogen components used for authoring greatly facilitate the integration of AR assistance systems. Furthermore, process data captured during inspections can optimize workflows by integrating usability metrics and operator feedback. Process digitalization and data analysis enable the identification of error-prone components and support refinements in inspection procedures, ultimately enhancing safety and efficiency in aviation maintenance.

5.4 Flexible assembly of aircraft interior components

Aircraft interior components, made from lightweight composite materials, are highly customized products since they serve 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. The combination of hardware for physical and cognitive assistance can enable a flexible and semi-automated assembly in the form of CPS, connecting the digital-modeled assembly process with the assembly station hardware in the real world. An example is shown in Fig. 5a, in which a cobot (physical assistance) is combined with a laser projection system (cognitive assistance) for the assembly of an aircraft cabin monument. Cobots, being inherently safe to operate in a human-robot shared workplace, can safely perform, e.g., pick-and-place operations for threaded inserts and attachments, serving as a third hand. In addition to pick-and-place tasks, tasks such as the precise application of adhesives can also be carried out with a cobot, which requires a high level of repeatability. Cobots increase the flexibility of an assembly station, primarily due to the intuitively online programming capabilities that allow for quick re-programming to new assembly variants. Projection-based assembly guidance relaxes the necessity of manually estimating a component's position and searching for the respective assembly instructions in digital or non-digital documentation (as shown in our example in Fig. 5b). For example, laser projectors can display visual assembly instructions, not only components' positions but also further instructions, directly onto the work surface, ensuring that components are assembled correctly. Furthermore, the commissioning of that hardware can be supported by using models of the processes and resources [61]. We refer the reader to [45] for further information on flexible assembly stations and the multi-variant assembly of aircraft interior components.

Concerning I5.0 technologies, examples in the literature show the use of individualized *human–machine interaction* technology but with a different focus than I5.0 suggests. So far, the objective of the approaches described above is to increase productivity to meet the growing demand for passenger aircraft. However, using semi-automated assembly systems can also be looked at from a human-centric perspective, improving ergonomics by reducing repetitive tasks and supporting unskilled workers when working on unfamiliar tasks. Furthermore, the model-based commission allows for the quick reconfiguration of existing resources to new

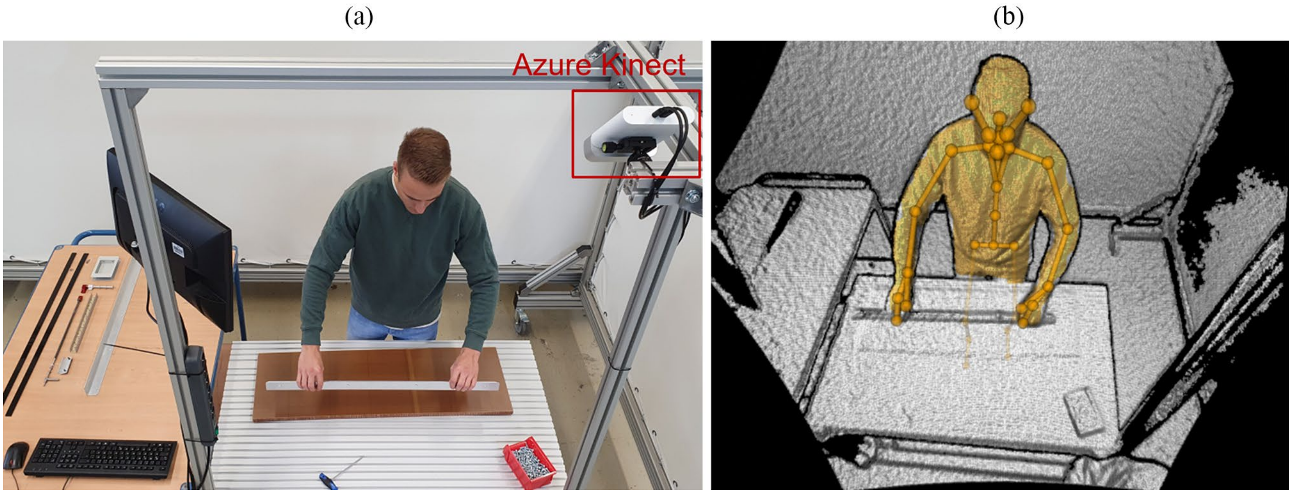

Fig. 6 **a** Workstation for multi-variant assembly processes in aircraft interior production; **b** Azure Kinect depth image and skeleton reconstruction [62]

products, which can result in 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 aviation industry's environmental impact by lowering fuel consumption. This can be met with flexible, hybrid assembly systems, adding economic value and enabling more ecological production with human-centric technologies.

5.5 Human Action Recognition (HAR)-based progress detection in manual assembly

Based on the use case described in the previous section, the flexible assembly of aircraft interior components and the investigation of manual assembly processes for multi-variant products are important I4.0 considerations. By introducing HRC [62], it is possible to increase both efficiency and flexibility within these processes. 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. Machines can decipher human movements, expressions, and verbal cues through advanced sensors and communication interfaces, allowing them to anticipate and respond to human needs more effectively [63]. HAR methods can establish such a communication channel from the human to the machine through movement tracking, in contrast to, e.g., performing gestures to confirm completed process steps, which are non-value-adding activities [62]. One core component of HAR is a sensor capable of perceiving humans in the process. Figure 6 depicts a HAR-ready workbench to assemble aircraft interior components (as described in the previous section). It is equipped with an Azure Kinect camera that outputs not only 2D-RGB images but also depth data. The Azure Kinect directly outputs skeleton reconstructions in a connected graph, in which nodes represent a human's joints. This graph can then be used to estimate actions over time and be mapped to the respective modeled assembly process. In a fixed-positioned assembly station, one camera can be sufficient, as shown in Fig. 6, compared to larger assembly stations, which can demand a set of cameras to cover the overall human working space. We refer the reader to [62, 63] for further information on the technical concepts behind the HAR-ready workbench.

Motivated by I4.0 key contents, the aforementioned *human–machine interaction* technology, HAR, can be used to detect the assembly progress non-invasively, which constitutes 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, we assign this particularly to the I5.0 idea of 'human-centric.' It enables a non-invasive process observation, which does not distract the worker's flow and can integrate the human into a digital process twin. As a result, HAR is an enabler for individual configurations of the workplace and robot programs, which includes exploiting human-individual process flexibilities 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 context of 'sustainability'. Since the developed HAR system is subject and process-independent, a possible adaptation to lot size one production enables productivity despite frequent changes in the product. Combined with the ability to adapt to different skill levels of workers, we can estimate that this will increase system resilience.

In the transformation from I4.0 to I5.0, HAR methods can make an important contribution to *human-centric solutions and human–machine interaction*, which interconnect and combine the strengths of humans and machines. Integrating the worker into a digital process twin is a prerequisite to addressing the worker's strengths, weaknesses, and other needs to develop a safe, inclusive process shifted to human-centricity.

5.6 In-progress monitoring systems

As already outlined in previous use cases, assembly processes in aircraft production are characterized by manual operations on a smaller to a larger scale. 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; therefore, value-added work is often 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 [64].

Optical sensor data can capture actions on the shop floor and digitalize processes that serve automated in-progress monitoring. The humans can then fully focus on their actual value-adding work. Meanwhile, continuous information flow and the empowerment of production control to react to deviations from the target state at an early stage are secured [65]. Progress monitoring relieves employees from time-consuming and recurring evaluation and data transmission tasks and reduces susceptibility to errors. The collected data can be compared with component and assembly models, process-relevant information, and deviations from the target state can be extracted. We reach a form of *human–machine interaction* when information derived from the actions on the shopfloor influences the process again through production control.

However, the implementation of an optical sensor system is a complex and time-consuming task [66], 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 [67], 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 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. Moreover, 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 system's configuration can also increase 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 [68]. 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 [69]. In addition to the barriers to automation, such as the size of the components or small lot sizes, the knowledge for identifying and classifying defects, e.g., for visual inspections or for carrying out processes with specific test equipment, is dependent on the knowledge of the human expert [70]. 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, counteract fluctuations of skilled employees, and to keep knowledge within the company. Although there are a few isolated approaches in the literature for the support of processes within the production of large components, such as fault management in shipbuilding [71], inspection [72], or assembly [73, 74] of large components, there is a lack of customizable assistance solutions motivated by the well-being of the worker in this environment.

Technologies that have been incorporated in these use cases are, e.g., mobile devices with capabilities of AR features and projection systems (light [75], laser [76], or video[77]), 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 I5.0's targeted human-centeredness through *human-centric solutions and human–machine interaction technologies*, it will be necessary to adapt these technologies even more to the individual to be supported [78]. 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

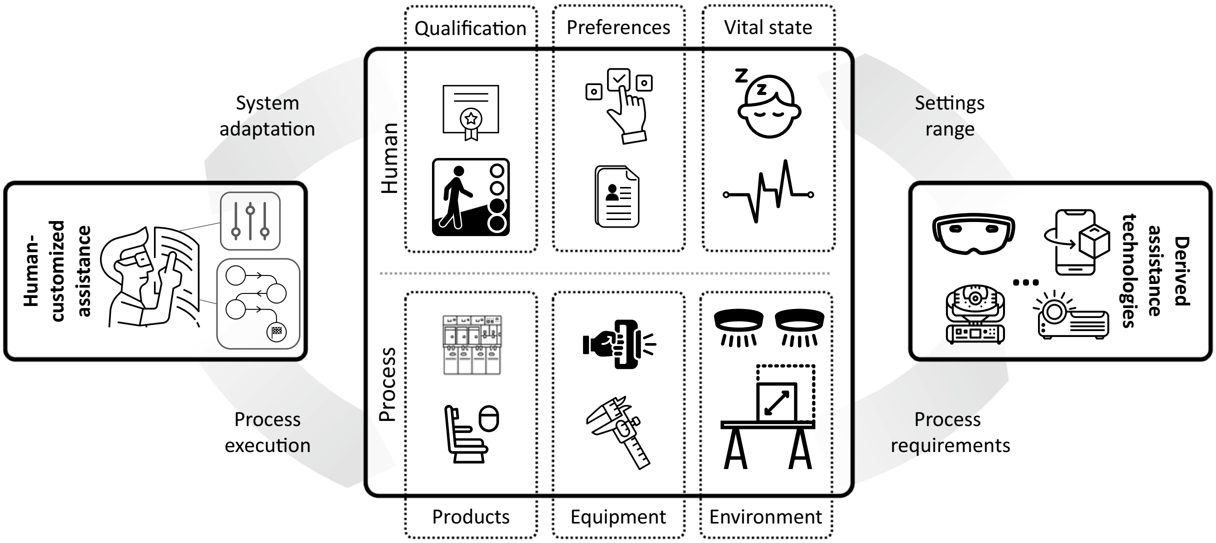

Fig. 7 Customizable assistance systems for manual inspections

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 [79] (see Fig. 7).

The strongly focused human-centeredness of I5.0 and, thus, the related improvement of working conditions will be driven even more strongly in 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 I4.0. An even better alignment of the available technologies with the people using them 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, the proven mechanisms of assistance systems, such as shortening learning times and reducing error rates, will be refined through feedback from users. In the aviation industry, which is characterized by a high demand for skilled workers, this will indirectly contribute to a higher resilience of manual processes.

6 Intralogistics

With up to 60% of all A320 components supplied by 12000 suppliers [80], 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 [81]. In the case of aircraft production and MRO, manufacturing facilities span multiple buildings and aircraft hangars. That is why intralogistics processes also extend across a large number of buildings and huge factory sites. Despite various I4.0 efforts to automate these intralogistics processes here and reduce the need for human labor, production and MRO supplying logistics are still largely carried out manually nowadays [82]. With challenges such as a variant-rich product spectrum [40], highly complex assembly scenarios [65, 67], 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 I5.0 principles. Figure 8 depicts an overview of the supply chain from suppliers to assembly. We have marked the use cases presented in the next sections accordingly.

6.1 Lean and flexible material supply

The delivery and supply of materials at the production site are often facilitated through 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. A streamlined material flow with an increased level of automation in such buffer zones, the introduction of small, modular, and transportable buffers, and direct delivery routing are beneficial for achieving a more sustainable and resilient delivery chain.

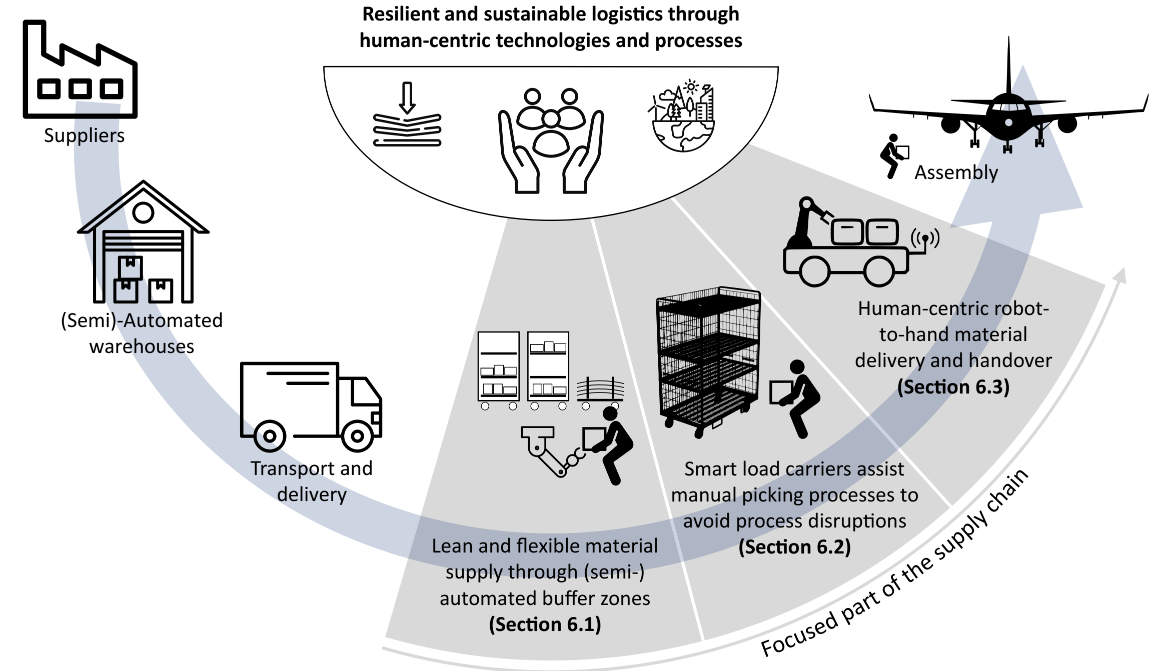

Fig. 8 Overview of the supply chain from suppliers to assembly and the intralogistics use cases (Sects. 6.1, 6.2, and 6.3) selected from it

Introducing semi-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, which results in a more human-assistive or *human-centric solution that combines the strengths of humans and machines*. The installation of IoT sensors along the delivery chain and the utilization of *data-driven algorithms and AI to detect anomalies*, as well as modern Warehouse Management Systems (WMS), which are capable of planning the next material picks, inventory placement, delivery routes, and estimating future material demand, makes it easier to adapt to disruptions and identify alternative routes quickly.

Challenges in semi-automated buffer zones include integrating human–machine interactions without disruption or disorder and gaining employee acceptance of automation. However, it enhances productivity by automating repetitive and simple tasks, enabling workers to focus on higher-value activities, reducing physical strain, and improving satisfaction on the job. Further, developing and implementing portable material buffers realized as dark storage systems outside the production facilities allow for achieving increased sustainability due to reduced space requirements within the buildings, less heating and climatization demands, and can help reduce transport distances and minimize commissioning and material-preparation processes. However, a combination of IoT sensor data, a WMS, and semi-automated material handling and delivery is a step forward towards a responsive and resilient on-site delivery chain.

6.2 Avoiding process disruptions through smart load carriers

Despite the desire to become more and more productive, workers have to perform many non-value-adding tasks in the logistics process chain. Trends in Big Data and I4.0 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 inputs 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 complex process chains and large assembly areas. Such unnecessary activities can lead to workforce frustration but can be avoided by introducing human-centric technologies.

Many I4.0 technologies need to be combined with technologies that are more associated with I5.0. Alternatively, they need to be rethought with human-centric values at their core. This involves taking familiar (technology-driven) concepts, e.g., the intelligent load carrier [83–86], and rethinking them in an I5.0 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, as a basis for *human–machine interaction*, 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 [83, 87] 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 *real time-based DTs* of the process [6] serve as the backbone for such systems, while *AI-based* visual applications may generate the necessary process updates [88, 89].

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 reliability - especially for AI-based systems - are challenges yet to overcome. Increasing such systems' pure Technology Readiness Level (TRL) can be associated with I4.0 aims, whereas I5.0 developments should increase the soft compatibility level with humans. Isolated technology developments cannot address these issues, but they have to be envisioned in a greater scope.

6.3 Human-centric material delivery and handover

As already indicated in the first use case (see Sect. 6.1), current delivery concepts for assembly stations often rely on designated PoDs using shelves and boxes for small materials [82] and specialized load carriers for bigger components and pipes. During assembly, an employee picks the material needed for the next assembly step from that PoD and collects the required tools.

Specialized cobot systems for HRC combined with DTs and simulations that reflect the current assembly progress can hand over tools and materials directly to the employee when required [85, 90]. Besides, as some of the assemblies require the technicians to work in non-ergonomic and uncomfortable positions, a demand-driven robot-to-hand material and tool delivery—an example of *human–machine interaction*—can significantly offer support and comfort. Such systems can then also support the lifting and handling of heavy materials.

With support in challenging assembly positions, e.g., over-head assembly, the technician can be relieved from the material collection and handling, allowing them to 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 robotics systems and fosters a better partnership between humans and robots. Such a human-centric working environment can help 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, DT models and simulations, which were especially motivated by I4.0, need to be adapted to not only reflect the product and its environment but also focus on the workers' current actions and demands.

7 MRO

MRO encompasses a comprehensive set of procedures to ensure an aircraft's continued airworthiness and operational readiness throughout its life. This complex 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 I5.0 ideas and concepts in composite structure repair, landing gear MRO, Nondestructive Testing (NDT), and repairing / overhauling / repurposing cabin interiors.

7.1 Virtual Reality (VR)-assisted 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

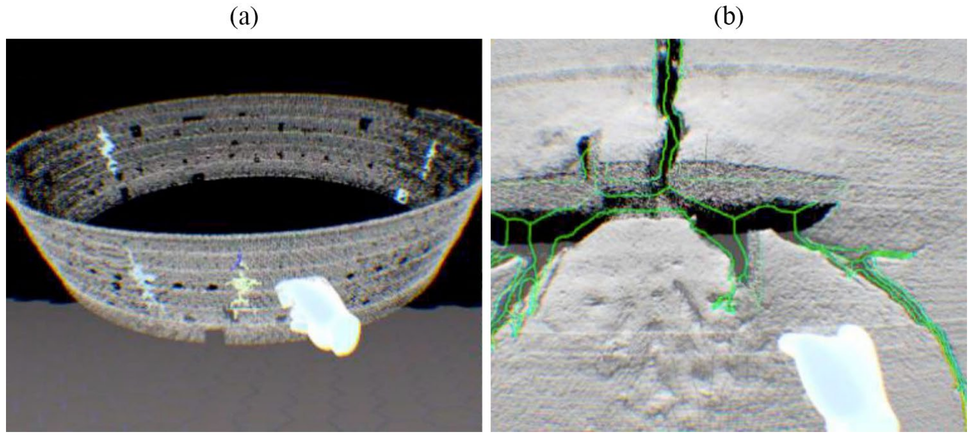

Fig. 9 **a** VR inspection of combustion chamber; **b** Typical defect [46]

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 [91]. 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.

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 VR [92–94], which is a technology for individualized *human–machine interaction*. Therefore, a VR-based inspection system, providing an immersive virtual environment for the assessment of scanning data (see Fig. 9), was developed [46].

Following the concept of I5.0, 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 VR 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 [95, 96]. While metal structures are usually repaired using doublers fastened by rivets, this method is not very appropriate for structural components made of Carbon Fiber-Reinforced Polymers (CFRP). 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 [97].

In order to facilitate the production of the scarf, reduce the time factor, and increase repeatability, a physical assistance system can aid the mechanic. An example of such a physical assistance system is depicted in Fig. 10a. It is a semi-automated milling system composed of an automated axis that controls the infeed of a milling tool and two further axes perpendicular to the infeed that 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 [98]. The system can be mounted onto a surface through suction cups, even on a curved aircraft fuselage (s. Figure 10b). This kind of system supports the concept of I5.0 mainly in terms of

(a) (b)

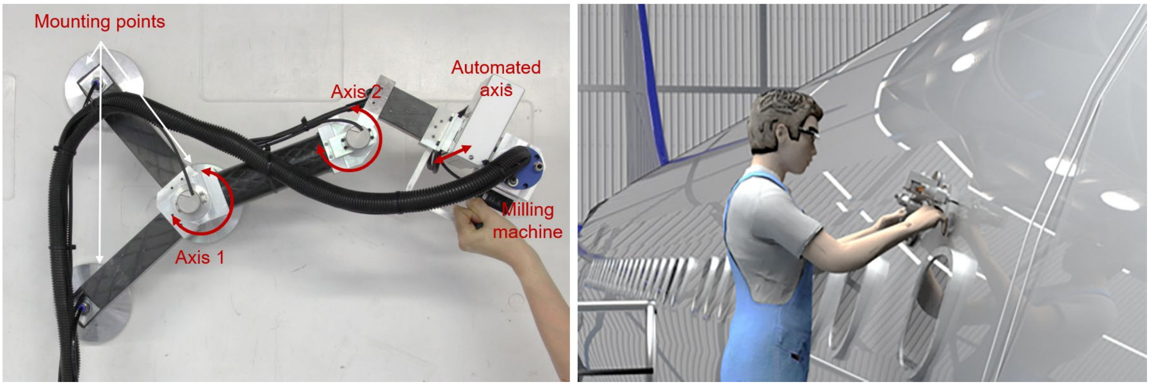

Fig. 10 **a** Physical assistance system for the repair of composite structures; **b** Usage on an aircraft fuselage

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) through a *human–machine interaction*.

The use of an 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 DT can be used at later times within the lifecycle 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.

7.3 AI-assisted inspections

In landing gear MRO, structural components are checked visually for any defects, such as cracks or corrosion [47]. In case of corrosion, the defect has to be removed, and the component has to be evaluated for reuse [99]. Inspections in aircraft MRO, as already outlined in 7.1, are time-consuming and especially safety-critical tasks, and a variety of technologies have been developed over the years to improve the process.

In the case of visual inspection, imaging sensors can be utilized, especially for difficult-to-access areas. Evaluating incoming images by means of AI 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 [100]. AI-assisted inspection enhances the human's cognitive capabilities, and since a final decision is made with the operator, it forms a *human-centric solution*. Automated defect removal by grinding with industrial robots 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 for special cases despite increased automation. 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 been considered irreplaceable, limiting overall resilience. Approaches using a decision tree and nearest neighbor algorithms may be used in 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, which also forms this a *human-centric solution*; therefore, these approaches are about providing a basis for decision-making.

In the context of I5.0, 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.

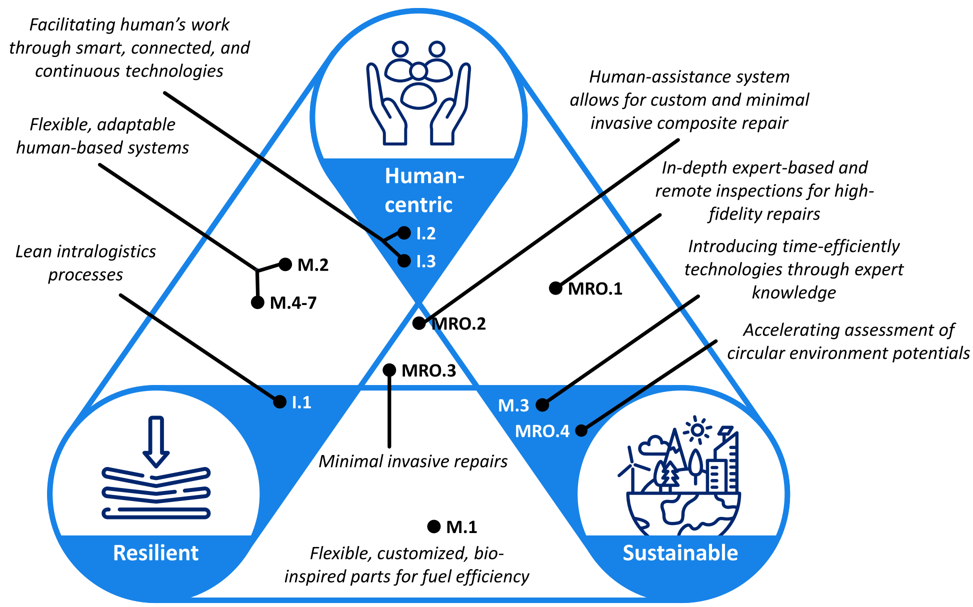

Fig. 11 This work's use cases and the related I5.0 core values (M: Manufacturing; MRO: Maintenance, Repair, and Overhaul; I: Intralogistics)

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 [101, 102]. 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.

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 [101] and AR systems [103], 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* so that the 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, which entails everything under the overarching concept of implementing a DT that replicates the real physical object instance following the I4.0 directive [101, 102, 104]. However, in the context of I5.0, the asset's DT 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 the physical instance.

8 Challenges and opportunities

8.1 Use cases summary

The use cases given in the previous sections target different facets of I5.0's core values. Summarizing these, as depicted in Fig. 11, with an effort to outline intersections, all three values, human-centric, resilient, and sustainable, are targeted with different extents and superimpositions.

The use cases from manufacturing (see Sects. 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., 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 H_2 systems, is a promising direction and targets sustainable values (see Sect. 5.3). Lastly, as already discussed, AM parts 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 for 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 I5.0 ideas in the context of valuing up intralogistics processes in the aircraft production and MRO domain are either increasing resilience through lean processes (see Sect. 6.1) or facilitating human work through smart, connected, and uniform technologies, thereby serving the idea of placing the human's demands back into the center (see Sects. 6.2-6.3).

Two of the use cases in MRO processes aim to minimize repair demands (see Sects. 7.2-7.3). A human-assisted system allows for minimal invasive repairs by fully utilizing expert knowledge. On the one hand, some argue that this approach restores value to humans by not completely replacing them; on the other hand, combining the universal and generalizable skills of humans with the strength, perseverance, and objectivity of machinery can significantly increase the resilience of the repair process/system. Moreover, concurrent digitalization or, at first, digitizing the object under test allows for remote assessments, reducing environmental travel expenses and minimizing the stress and strain of time-consuming travel on the operator (see Sect. 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 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 to implement I5.0 principles in the context of aircraft production and MRO.

8.2 Enabling technologies

Working towards the I5.0 core values of human-centricity, sustainability, and resilience, different already existing and future technologies enable applications. As this work already uses a case-driven approach, multiple technologies exist, but only a few have been proven and evaluated at a high TRL. The next subsections will discuss individual enabling technologies in the aircraft production domain following the taxonomy from a workshop with European industrial leaders (see Sect. 2.2.2). This discussion is based on the insights gained from the use cases presented in this work while acknowledging that additional enabling technologies may also exist outside the scope of this analysis. Out of the six enabling technology categories (see Sect. 2.2.2), the four categories mentioned in the next subsections are, from our point of view, the most prominent and relevant in the context of aircraft production and MRO. While *cyber-secure data transmission, storage, and analysis* capable of secure data handling are certainly important topics, from the perspective of research gaps in aircraft production and MRO process-near applications, they are often already lived practice. Similarly, technologies for *energy efficiency and trustworthy autonomy*, while essential, are more relevant to the product aircraft itself rather than the production and MRO infrastructure. From our perspective, it addresses the need for reliable autonomy in operating aircraft across the globe, less the production and MRO infrastructure.

8.2.1 Individualized 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 such as multilingual speech and gesture recognition capture a human's current action or state (see Sect. 5.5) and are considered at TRL 5–6, but as shown in the use case, are not actually implemented in current industries. Also, tracking technologies to automatically assess the physical strain and stress of employees 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 Sect. 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 (see Sects. 5.2-5.3). However, the shift in paradigms during the progression from I4.0 to I5.0, namely the evolution from an efficiency-oriented digitalization 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 assistance applications (AR or other technologies), thus emphasizing the necessity of extended research within the domain of industrial assistance systems and the underlying human–machine interaction.

The complementary to cognitive assistance is physical assistance through mechanical actuators, e.g., in the form of collaborative robots, which are online teachable and 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.

8.2.2 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 [105]. Although recent advantages made 3D printing for metallic components both economically feasible and aviation safety compliable, increasing the TRL for composite structure 3D printing (see Sect. 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 lifecycle and the high value of existing aircraft, this is a slow-paced contribution to a sustainable aviation industry.

In the meantime, e.g., the bio-inspired *AeroShark* [106] 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.

8.2.3 DTs and simulation

DTs digitally replicate a physical asset, instance-wise, to enable applications such as simulations. For example, the idea is to first test and simulate modifications of an existing system in a virtual environment before introducing changes into the real world. The implementation of a holistic DT of a complete aircraft or an aircraft final assembly line is theoretically ideal, as products and processes are often not digitally modeled, and many different types and dynamic multi-scale models are required. Also, focusing on incorporating the human part, the concept of a 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 HRC 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 as a result of having to process large amounts of data. Instead of dealing with a holistic digitally enabling system, purpose-bound and domain-specific, data and information can be used to replicate (sub-)systems [6]. This basis may then serve as the enabling technology for further applications that fulfill the core values of human centricity, working, and operational safety.

8.2.4 AI

Future advances in AI have the potential to benefit many aspects of aviation. Excluding applications such as optimized flight path routing and passenger guidance, the presented use cases consider AI as a tool to support future production aspects, including interactive and autonomous responses of robots and assistance systems. 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 Sect. 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 DTs, as discussed above. However, AI is only able to optimize entire process chains if granted access to appropriate databases.

8.3 Discussion and outlook

Since the beginning of this century, industries have faced various societal and environmental challenges, and the COVID-19 pandemic-related shutdowns have shaped the latest most significant interruption. Among many other actions, a governmental, EU-backed response was formulating and standardizing a new terminology as a complement to I4.0. The I5.0 values—human-centric, sustainable, and resilient—now aim to prioritize values in the industrial sector to influence the direction of campaigns, funding, research, and development. The traditional objective of increasing productivity will not succeed in winning the markets of the future, especially in light of demographic change, and when industries have to take full responsibility for the current and future environmental impact of their products. To find a common term for this, we have introduced *Consideration* as an overarching I5.0 representation (see Fig. 2). I5.0 ponders the various societal, environmental, and deductivating industrial needs. In addition to the definitions given by the EU, we encourage current research to work on an I5.0 reference architecture/framework to be able to name, measure, and classify I5.0 added value in a standardized way, but also to be guided in the three value directions.

Moreover, future work could involve conducting a systematic literature review and interviews with experts to evaluate a more extensive variety of I5.0 use cases. This could enable a more comprehensive understanding of the I5.0 principles' potential and allow for the development of further recommendations in the domain and accessing technology's TRLs, as, e.g., done in [107] in the context of I4.0.

Strictly speaking, current aircraft production and MRO market companies are not using the I5.0 terminologies but are already working on various aspects of the transformation from technology-driven to value-driven concepts without explicitly stating so. As we have outlined in the various use cases, the aircraft industry as a whole is grappling with the complex requirements of I5.0. However, previous research and development topics on technologies already partially fulfill the core values of I5.0 in various aspects, although they may be required to be redefined or rethought in their application. All industrial revolutions have been made possible by the development of novel technologies, as will I5.0, but their use may differ from I4.0.

In 2011, Europe's Flightpath 2050 introduced the notion of serving society's needs in addition to maintaining global leadership [108], thus targeting an I5.0 core value of protecting the environment and leading, e.g., to Airbus' current H_2-based aviation research and development efforts. Here, further research is needed to take new technologies and novel applications to the next level and introduce them on a larger scale. On the one hand, it is interesting to develop existing approaches and technologies further, as outlined in the use cases, especially in the intralogistics, repair, and overhaul markets. Aircraft fleets are not replaced on a day-to-day basis, so the overhaul and retrofitting of existing (sub-)systems must be targeted with the aim of achieving sustainable values. In this case, human-centricity and resilience values follow this core objective. On the other hand, disruptive changes in the product aircraft require flexible, adaptable production systems capable of bringing new technologies to market in a timely manner—ramp-ups must be shortened. Many bright minds will be shaping the technologies of the future, and the I5.0 idea encourages them to focus on the three core values rather than just increasing production efficiency, which would further exacerbate contemporary social and environmental challenges.

In conclusion, 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. Therefore, it needs to take 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.

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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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References

1. Vogel-Heuser, B., Bauernhansl, T., Ten Hompel, M. (eds.): Handbuch Industrie 4.0 Bd.4: Allgemeine Grundlagen. Springer, Berlin, Heidelberg (2017). https://doi.org/10.1007/978-3-662-53254-6
2. European Commission. Directorate General for Research and Innovation.: Enabling Technologies for Industry 5.0: Results of a Workshop with Europe's Technology Leaders. Publications Office, LU (2020). https://data.europa.eu/doi/10.2777/082634. Accessed 24 Jul 2023

3. European Commission. Directorate General for Research and Innovation.: Industry 5.0: Towards a Sustainable, Human Centric and Resilient European Industry. Publications Office, LU (2021). https://data.europa.eu/doi/10.2777/308407. Accessed 24 Jul 2023
4. European Commission. Directorate General for Research and Innovation.: Industry 5.0: Human Centric, Sustainable and Resilient. Publications Office, LU (2020). https://data.europa.eu/doi/10.2777/073781. Accessed 24 Jul 2023
5. Hinsch, M.: Industrial Aviation Management: A Primer in European Design, Production and Maintenance Organisations. Springer, Berlin, Heidelberg (2019). https://doi.org/10.1007/978-3-662-54740-3
6. Moenck, K., Rath, J.-E., Koch, J., Wendt, A., Kalscheuer, F., Schüppstuhl, T., Schoepflin, D.: Digital twins in aircraft production and MRO: Challenges and opportunities. CEAS Aeronautical Journal (2024). https://doi.org/10.1007/s13272-024-00740-y
7. Reinhart, G. (ed.): Handbuch Industrie 4.0: Geschäftsmodelle, Prozesse, Technik. Carl Hanser Verlag GmbH & Co. KG, München (2017). https://doi.org/10.3139/9783446449893
8. Eschen, H., Kalscheuer, F., Schüppstuhl, T.: Optimized process chain for flexible and automated aircraft interior production. Procedia Manufacturing **51**, 535–542 (2020). https://doi.org/10.1016/j.promfg.2020.10.075
9. Kähler, F., Eschen, H., Schüppstuhl, T.: Automated Installation of Inserts in Honeycomb Sandwich Materials. Procedia Manufacturing **51**, 462–469 (2020). https://doi.org/10.1016/j.promfg.2020.10.065
10. Ehrbar, J., Kähler, F., Schüppstuhl, T.: Automated assessment for grinding spots on aircraft landing gear components using robotic white light interferometry. In: Lehmann, P., Osten, W., Albertazzi Gonçalves, A. (eds.) Optical Measurement Systems for Industrial Inspection XIII, p. 96. SPIE, Munich, Germany (2023). https://doi.org/10.1117/12.2673757
11. Bath, L., Dammann, M., Schüppstuhl, T.: Circular Path Generation for Toroidal Cavity Inspection. In: Schüppstuhl, T., Tracht, K., Henrich, D. (eds.) Annals of Scientific Society for Assembly, Handling and Industrial Robotics, pp. 205– 215. Springer, Berlin, Heidelberg (2020). https://doi.org/10.1007/978-3-662-61755-7_19
12. Dammann, M., Schüppstuhl, T.: Automated selection and assembly of sets of blades for jet engine compressors and turbines. Procedia Manufacturing **16**, 53–60 (2018). https://doi.org/10.1016/j.promfg.2018.10.159
13. Belhadi, A., Kamble, S., Jabbour, C., Gunasekaran, A., Ndubisi, N.O., Venkatesh, M.: Manufacturing and service supply chain resilience to the COVID-19 outbreak: Lessons learned from the automobile and airline industries. Technol. Forecast. Soc. Chang. **163**, 120447 (2021). https://doi.org/10.1016/j.techfore.2020.120447
14. Bohnsack, A.: Spinnen und Weben: Entwicklung Von Technik und Arbeit Im Textilgewerbe, Orig.-ausg edn. Kulturgeschichte der Naturwissenschaften und der Technik, vol. Bd. 2. Rowohlt, Reinbek bei Hamburg (1981)
15. Nahavandi, S.: Industry 5.0-A Human-Centric Solution. Sustainability **11**(16), 4371 (2019). https://doi.org/10.3390/su11164371
16. Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final report of the Industrie 4.0 Working Group. https://en.acatech.de/publication/recommendations-for-implementing-the-strategic-initiative-industrie-4-0-final-report-of-the-industrie-4-0-working-group/ Accessed 30 Aug 2023
17. Orders and deliveries | Boeing (2021). https://www.boeing.com/commercial/#/orders-deliveries Accessed 30 Aug 2023
18. Orders and deliveries | Airbus (2021). https://www.airbus.com/en/products-services/commercial-aircraft/market/orders-and-deliveries Accessed 30 Aug 2023
19. ZEROe - Low carbon aviation - Airbus (2021). https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe Accessed 30 Aug 2023
20. Bischoff, J., Taphorn, C., Wolter, D., Braun, N., Fellbaum, M., Goloverov, A., Ludwig, S., Hegmanns, T., Prasse, C., Henke, M., Ten Hompel, M., Döbbeler, F., Fuss, E., Kirsch, C., Mättig, B., Braun, S., Guth, M., Kaspers, M., Scheffler, D.: Erschließen der Potenziale der Anwendung von Industrie 4.0 im Mittelstand (2015). https://publica.fraunhofer.de/handle/publica/297414 Accessed 230 Aug 2023
21. Ten Hompel, M., Vogel-Heuser, B., Bauernhansl, T. (eds.): Handbuch Industrie 4.0: Produktion, Automatisierung und Logistik. Springer, Berlin, Heidelberg (2020). https://doi.org/10.1007/978-3-662-45537-1
22. Leng, J., Sha, W., Wang, B., Zheng, P., Zhuang, C., Liu, Q., Wuest, T., Mourtzis, D., Wang, L.: Industry 5.0: Prospect and retrospect. J. Manuf. Syst. **65**, 279–295 (2022). https://doi.org/10.1016/j.jmsy.2022.09.017
23. Huang, S., Wang, B., Li, X., Zheng, P., Mourtzis, D., Wang, L.: Industry 5.0 and Society 5.0 - Comparison, complementation and co-evolution. J. Manuf. Syst. **64**, 424–428 (2022). https://doi.org/10.1016/j.jmsy.2022.07.010
24. Xu, X., Lu, Y., Vogel-Heuser, B., Wang, L.: Industry 4.0 and Industry 5.0 - Inception, conception and perception. J. Manuf. Syst. **61**, 530–535 (2021). https://doi.org/10.1016/j.jmsy.2021.10.006
25. Welfare, K.S., Hallowell, M.R., Shah, J.A., Riek, L.D.: Consider the Human Work Experience When Integrating Robotics in the Workplace. In: 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI), pp. 75–84. IEEE, Daegu, Korea (South) (2019). https://doi.org/10.1109/HRI.2019.8673139
26. Østergaard, E.H.: WELCOME TO INDUSTRY 5.0 - The human touch revolution is now under way. https://www.universal-robots.com/ Accessed 10 Sep 2024
27. Demir, K.A., Döven, G., Sezen, B.: Industry 5.0 and Human-Robot Co-working. Procedia Computer Science **158**, 688–695 (2019). https://doi.org/10.1016/j.procs.2019.09.104
28. Özdemir, V., Hekim, N.: Birth of Industry 5.0: Making Sense of Big Data with Artificial Intelligence, "The Internet of Things" and Next-Generation Technology Policy. OMICS **22**(1), 65–76 (2018). https://doi.org/10.1089/omi.2017.0194
29. Wang, B., Zheng, P., Yin, Y., Shih, A., Wang, L.: Toward human-centric smart manufacturing: A human-cyber-physical systems (HCPS) perspective. J. Manuf. Syst. **63**, 471–490 (2022). https://doi.org/10.1016/j.jmsy.2022.05.005
30. Zhou, J., Zhou, Y., Wang, B., Zang, J.: Human-Cyber-Physical Systems (HCPSs) in the Context of New-Generation Intelligent Manufacturing. Engineering **5**(4), 624–636 (2019). https://doi.org/10.1016/j.eng.2019.07.015
31. Chen, X., Eder, M.A., Shihavuddin, A., Zheng, D.: A Human-Cyber-Physical System toward Intelligent Wind Turbine Operation and Maintenance. Sustainability **13**(2), 561 (2021). https://doi.org/10.3390/su13020561
32. Wang, B., Zhou, H., Yang, G., Li, X., Yang, H.: Human Digital Twin (HDT) Driven Human-Cyber-Physical Systems: Key Technologies and Applications. Chinese Journal of Mechanical Engineering **35**(1), 11 (2022). https://doi.org/10.1186/s10033-022-00680-w
33. Wang, L.: A futuristic perspective on human-centric assembly. J. Manuf. Syst. **62**, 199–201 (2022). https://doi.org/10.1016/j.jmsy.2021.11.001
34. European Commission. Directorate General for Research and Innovation.: Categorisation System for the Circular Economy: a Sector Agnostic Categorisation System for Activities Substantially Contributing to the Circular Economy. Publications Office,

LU (2020). https://data.europa.eu/doi/10.2777/172128. Accessed 16 Aug 2023
35. Adlin, N., Lanz, M., Lohtander, M.: The Circular Economy Competence of the Manufacturing Sector - A Case Study. In: Kim, K.-Y., Monplaisir, L., Rickli, J. (eds.) Flexible Automation and Intelligent Manufacturing: The Human-Data-Technology Nexus, pp. 351– 360. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-18326-3_34
36. Li, X., Wang, B., Peng, T., Xu, X.: Greentelligence: Smart Manufacturing for a Greener Future. Chinese Journal of Mechanical Engineering **34**(1), 116 (2021). https://doi.org/10.1186/s10033-021-00656-2
37. Miehe, R., Bauernhansl, T., Schwarz, O., Traube, A., Lorenzoni, A., Waltersmann, L., Full, J., Horbelt, J., Sauer, A.: The biological transformation of the manufacturing industry - envisioning biointelligent value adding. Procedia CIRP **72**, 739–743 (2018). https://doi.org/10.1016/j.procir.2018.04.085
38. Wildemann, H., Hojak, F.: Main differences and commonalities between the aircraft and the automotive industry. In: Richter, K., Walther, J. (eds.) Supply Chain Integration Challenges in Commercial Aerospace, pp. 119– 138. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-46155-7_9
39. Lukaszewicz, D.H.-J.A., Ward, C., Potter, K.D.: The engineering aspects of automated prepreg layup: History, present and future. Compos. B Eng. **43**(3), 997–1009 (2012). https://doi.org/10.1016/j.compositesb.2011.12.003
40. Eschen, H., Harnisch, M., Schüppstuhl, T.: Flexible and automated production of sandwich panels for aircraft interior. Procedia Manufacturing **18**, 35–42 (2018). https://doi.org/10.1016/j.promfg.2018.11.005
41. Aircraft, A.C.: Airbus inaugurates new A320 structure assembly line in Hamburg (2019). https://www.airbus.com/en/newsroom/press-releases/2019-10-airbus-inaugurates-new-a320-structure-assembly-line-in-hamburg Accessed 25 Aug 2023
42. Berschik, M.C., Blecken, M., Kumawat, H., Rath, J.-E., Krause, D., God, R., Schüppstuhl, T.: A holistic aircraft cabin metamodel as an approach towards an interconnected digitised cabin lifecycle **10**(15480/882), 4757 (2022)
43. Rath, J.-E., Koch, J., Schüppstuhl, T.: Towards Model-Based Assembly System Configuration Supported by SysML and AutomationML. In: Silva, F.J.G., Pereira, A.B., Campilho, R.D.S.G. (eds.) Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems, pp. 622– 632. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-38241-3_70
44. Koch, J., Eggers, K., Rath, J.-E., Schüppstuhl, T.: Development Process for Information Security Concepts in IIoT-Based Manufacturing. In: Kim, K.-Y., Monplaisir, L., Rickli, J. (eds.) Flexible Automation and Intelligent Manufacturing: The Human-Data-Technology Nexus, pp. 316– 331. Springer, Cham (2023).https://doi.org/10.1007/978-3-031-18326-3_31
45. Kalscheuer, F., Eschen, H., Schüppstuhl, T.: Towards Semi Automated Pre-assembly for Aircraft Interior Production. In: Schüppstuhl, T., Tracht, K., Raatz, A. (eds.) Annals of Scientific Society for Assembly, Handling and Industrial Robotics 2021, pp. 203– 213. Springer, Cham (2022).https://doi.org/10.1007/978-3-030-74032-0_17
46. Eschen, H., Kötter, T., Rodeck, R., Harnisch, M., Schüppstuhl, T.: Augmented and Virtual Reality for Inspection and Maintenance Processes in the Aviation Industry. Procedia Manufacturing **19**, 156–163 (2018). https://doi.org/10.1016/j.promfg.2018.01.022
47. Kähler, F., Schmedemann, O., Schüppstuhl, T.: Anomaly detection for industrial surface inspection: application in maintenance of aircraft components. Procedia CIRP **107**, 246–251 (2022). https://doi.org/10.1016/j.procir.2022.05.197
48. Aircraft, A.C.: ZEROe. Towards the world's first hydrogen-powered commercial aircraft (2021). https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe Accessed 25 Aug 2023
49. Forster, E., Clay, S., Holzwarth, R., Paul, D.: Flight Vehicle Composite Structures. In: The 26th Congress of ICAS and 8th AIAA ATIO. American Institute of Aeronautics and Astronautics, Anchorage, Alaska (2008). https://doi.org/10.2514/6.2008-8976
50. Marsh, G.: Boeing's 787: trials, tribulations, and restoring the dream. Reinf. Plast. **53**(8), 16–21 (2009). https://doi.org/10.1016/S0034-3617(09)70311-X
51. Mei, Z., Maropoulos, P.G.: Review of the application of flexible, measurement-assisted assembly technology in aircraft manufacturing. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture **228**(10), 1185–1197 (2014). https://doi.org/10.1177/0954405413517387
52. Sarh, B., Buttrick, J., Munk, C., Bossi, R.: Aircraft Manufacturing and Assembly. In: Nof, S.Y. (ed.) Springer Handbook of Automation, pp. 893– 910. Springer, Berlin, Heidelberg (2009). https://doi.org/10.1007/978-3-540-78831-7_51
53. Goh, G.D., Yap, Y.L., Agarwala, S., Yeong, W.Y.: Recent Progress in Additive Manufacturing of Fiber Reinforced Polymer Composite. Advanced Materials Technologies **4**(1), 1800271 (2019). https://doi.org/10.1002/admt.201800271
54. Liu, G., Xiong, Y., Zhou, L.: Additive manufacturing of continuous fiber reinforced polymer composites: Design opportunities and novel applications. Composites Communications **27**, 100907 (2021). https://doi.org/10.1016/j.coco.2021.100907
55. Kipping, J., Kállai, Z., Schüppstuhl, T.: A Set of Novel Procedures for Carbon Fiber Reinforcement on Complex Curved Surfaces Using Multi Axis Additive Manufacturing. Appl. Sci. **12**(12), 5819 (2022). https://doi.org/10.3390/app12125819
56. Kipping, J., Schüppstuhl, T.: Load-Oriented Nonplanar Additive Manufacturing Method for Optimized Continuous Carbon Fiber Parts. Materials **16**(3), 998 (2023). https://doi.org/10.3390/ma16030998
57. Pakdel, E., Kashi, S., Varley, R., Wang, X.: Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes. Resour. Conserv. Recycl. **166**, 105340 (2021)
58. Wulff, L.A., Brand, M., Schüppstuhl, T.: Usability of Augmented Reality Assisted Commissioning of Industrial Robot Programs. In: Schüppstuhl, T., Tracht, K., Fleischer, J. (eds.) Annals of Scientific Society for Assembly, Handling and Industrial Robotics 2022, pp. 91– 102. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-10071-0_8
59. Masuhr, C., Büsch, L., Schüppstuhl, T.: Leakage Inspection for the Scale-Up of Hydrogen Electrolyzers: A Case Study and Comparative Analysis of Technologies. In: Silva, F.J.G., Pereira, A.B., Campilho, R.D.S.G. (eds.) Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems, pp. 496– 508. Springer, Cham (2024).https://doi.org/10.1007/978-3-031-38241-3_56
60. Williams, G., Gheisari, M., Chen, P.-J., Irizarry, J.: BIM2MAR: An Efficient BIM Translation to Mobile Augmented Reality Applications. J. Manag. Eng. **31**(1), 4014009 (2015). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000315
61. Kalscheuer, F., Koch, J., Schüppstuhl, T.: Reducing commissioning efforts for hybrid assembly systems using a data-driven approach. Procedia CIRP **118**, 935–939 (2023). https://doi.org/10.1016/j.procir.2023.06.161
62. Koch, J., Büsch, L., Gomse, M., Schüppstuhl, T.: A Methods-Time-Measurement based Approach to enable Action Recognition for Multi-Variant Assembly in Human-Robot Collaboration. Procedia CIRP **106**, 233–238 (2022). https://doi.org/10.1016/j.procir.2022.02.184

63. Büsch, L., Koch, J., Schoepflin, D., Schulze, M., Schüppstuhl, T.: Towards Recognition of Human Actions in Collaborative Tasks with Robots: Extending Action Recognition with Tool Recognition Methods. Sensors **23**(12), 5718 (2023). https://doi.org/10.3390/s23125718
64. Andrianakos, G., Dimitropoulos, N., Michalos, G., Makris, S.: An approach for monitoring the execution of human based assembly operations using machine learning. Procedia CIRP **86**, 198–203 (2019). https://doi.org/10.1016/j.procir.2020.01.040
65. Gierecker, J., Kalscheuer, F., Schoepflin, D., Schüppstuhl, T.: Automated CAD-based sensor planning and system implementation for assembly supervision. Procedia CIRP **118**, 930–934 (2023). https://doi.org/10.1016/j.procir.2023.06.160
66. Jørgensen, T.B., Iversen, T.M., Lindvig, A.P., Schlette, C., Kraft, D., Savarimuthu, T.R., Rossmann, J., Krüger, N.: Simulation-based Optimization of Camera Placement in the Context of Industrial Pose Estimation. In: Imai, F., Tremeau, A., Braz, J. (eds.) VISIGRAPP 2018: Proceedings of the 13th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications : Funchal, Madeira, Portugal, January 27-29, 2018, pp. 524– 533. SCITEPRESS - Science and Technology Publications Lda, Setúbal, Portugal (2018). https://doi.org/10.5220/0006553005240533
67. Gierecker, J., Schüppstuhl, T.: Assembly specific viewpoint generation as part of a simulation based sensor planning pipeline. Procedia CIRP **104**, 981–986 (2021). https://doi.org/10.1016/j.procir.2021.11.165
68. Koch, J., Lotzing, G., Eschen, H., Moenck, K., Schüppstuhl, T.: A human-centered iiot platform approach for manual inspections: Towards digital documentation and assistance applications. Procedia CIRP **120**, 762–767 (2023). https://doi.org/10.1016/j.procir.2023.09.072
69. Mosca, N., Renò, V., Nitti, M., Patruno, C., Stella, E.: Post assembly quality inspection using multimodal sensing in aircraft manufacturing. In: Multimodal Sensing and Artificial Intelligence: Technologies and Applications II **11785**, 188–195 (2021). https://doi.org/10.1117/12.2594104.
70. Chen, W., Huang, S.: Human reliability analysis for visual inspection in aviation maintenance by a bayesian network approach. Transportation Research Record: Journal of the Transportation Research Board **2449**(1), 105–113 (2014). https://doi.org/10.3141/2449-12
71. Jahn, N., Jansen, T., Rost, R., Lödding, H.: Disruption Management in One-Off Production with Collaborative Digital Assistance Systems - Benefits of an Integrative Approach with a Generic Data Model. In: Plapper, P. (ed.) Digitization of the Work Environment for Sustainable Production, pp. 171– 192. GITO Verlag, Berlin (2022). https://doi.org/10.30844/WGAB_2022_9
72. Koch, J., Jevremovic, D., Schüppstuhl, T.: Mobile Web App for the Digitization and Annotation of Manual Visual Inspection Tasks. Procedia CIRP **126**, 993–998 (2024). https://doi.org/10.1016/j.procir.2024.08.373
73. Rupprecht, P.: Spatial Augmented Reality in der industriellen Großgeräte- und Baustellenmontage: Entwicklung eines Assistenzsystems mit dynamischer In-situ-Projektion und nutzeradaptiver Gesteninteraktion. PhD thesis, TU Wien (2022). https://doi.org/10.34726/HSS.2022.53621
74. Piontek, S., Lödding, H.: User-centric digital assistance with smart tools for manual assembly processes. In: Kim, D.Y., Cieminski, G., Romero, D. (eds.) Advances in Production Management Systems. Smart Manufacturing and Logistics Systems: Turning Ideas Into Action. Springer eBook Collection, vol. 663, pp. 101– 109. Springer Nature Switzerland and Imprint Springer, Cham (2022). https://doi.org/10.1007/978-3-031-16407-1_13
75. Koch, J., Büchse, C., Schüppstuhl, T.: Development and Integration of a Workpiece-Based Calibration Method for an Optical Assistance System. Appl. Sci. **13**(13), 7369 (2023). https://doi.org/10.3390/app13137369
76. Müller, R., Hörauf, L., Vette-Steinkamp, M., Kanso, A., Koch, J.: The Assist-By-X system: Calibration and application of a modular production equipment for visual assistance. Procedia CIRP **86**, 179–184 (2019). https://doi.org/10.1016/j.procir.2020.01.021
77. Funk, M.: Augmented reality at the workplace: a context-aware assistive system using in-situ projection. PhD thesis (2016). https://doi.org/10.18419/opus-8997
78. Romero, D., Stahre, J.: Towards the resilient operator 5.0: The future of work in smart resilient manufacturing systems. Procedia CIRP **104**, 1089–1094 (2021). https://doi.org/10.1016/j.procir.2021.11.183
79. Niklas Breitkopf: Adaptive Assistenz in der Produktion. Schriftenreihe des Lehrstuhls für Produktionssysteme, vol. 2018,2. Shaker Verlag, Aachen (2018)
80. Ebner, U.: Airbus-Zulieferer: Viele Geburtshelfer für eine A320 (2021). https://www.flugrevue.de/a320-zulieferer-gemeinschaftswerk/ Accessed 30 Aug 2023
81. Arnold, D. (ed.): Intralogistik. Springer, Berlin, Heidelberg (2006). https://doi.org/10.1007/978-3-540-29658-4
82. Sliwinski, M., Raabe, C., Thiel, M., Hinckeldeyn, J., Kreutzfeldt, J.: Entwicklung eines modularen Ladungsträgers für Euronormbehälter für die Flugzeugproduktion. Volume 2019, 12 (2019) https://doi.org/10.2195/LJ_PROC_SLIWINSKI_DE_201912_01
83. Schoepflin, D., Koch, J., Gomse, M., Schüppstuhl, T.: Smart Material Delivery Unit for the Production Supplying Logistics of Aircraft. Procedia Manufacturing **55**, 455–462 (2021). https://doi.org/10.1016/j.promfg.2021.10.062
84. Bertram, P., Motsch, W., Rübel, P., Ruskowski, M.: Intelligent Material Supply Supporting Assistive Systems for Manual Working Stations. Procedia Manufacturing **38**, 983–990 (2019). https://doi.org/10.1016/j.promfg.2020.01.182
85. Castro, A., Silva, F., Santos, V.: Trends of Human-Robot Collaboration in Industry Contexts: Handover, Learning, and Metrics. Sensors **21**(12), 4113 (2021). https://doi.org/10.3390/s21124113
86. Müller, R., Vette-Steinkamp, M., Hörauf, L., Speicher, C., Burkhard, D.: Development of an Intelligent Material Shuttle to Digitize and Connect Production Areas with the Production Process Planning Department. Procedia CIRP **72**, 967–972 (2018). https://doi.org/10.1016/j.procir.2018.03.216
87. Rammelmeier, T., Galka, S., Günthner, W.A.: Fehlervermeidung in der Kommissionierung. Logistics Journal **2012**(01) (2012) https://doi.org/10.2195/lj_Proc_rammelmeier_de_201210_01
88. Schoepflin, D., Albayrak, O., Scheffler, P., Wendt, A., Gomse, M., Schuppstuhl, T.: Visual AI Applications on Smart Delivery Units. In: 2021 IEEE Global Conference on Artificial Intelligence and Internet of Things (GCAIoT), pp. 19– 24. IEEE, Dubai, United Arab Emirates (2021) https://doi.org/10.1109/GCAIoT53516.2021.9693060
89. Schoepflin, D., Holst, D., Gomse, M., Schüppstuhl, T.: Synthetic Training Data Generation for Visual Object Identification on Load Carriers. Procedia CIRP **104**, 1257–1262 (2021). https://doi.org/10.1016/j.procir.2021.11.211
90. Kupcsik, A., Hsu, D., Lee, W.S.: Learning Dynamic Robot-to-Human Object Handover from Human Feedback. In: Bicchi, A., Burgard, W. (eds.) Robotics Research **2**, 161–176 (2018). https://doi.org/10.1007/978-3-319-51532-8_10.
91. Domaschke, T.: Automatisierung der Weißlichtinterferometrie zur Inspektion rotationssymmetrischer Triebwerksbauteile. PhD thesis, Dr. Hut GmbH (December 2017). https://doi.org/10.15480/882.1501

92. Bacim, F., Ragan, E., Scerbo, S., Polys, N.F., Setareh, M., Jones, B.D.: The effects of display fidelity, visual complexity, and task scope on spatial understanding of 3D graphs. Proceedings of Graphics Interface **2**(1) (2013)
93. Laha, B., Sensharma, K., Schiffbauer, J.D., Bowman, D.A.: Effects of Immersion on Visual Analysis of Volume Data. IEEE Trans. Visual Comput. Graphics **18**(4), 597–606 (2012). https://doi.org/10.1109/TVCG.2012.42
94. Laha, B., Bowman, D.A., Socha, J.J.: Effects of VR System Fidelity on Analyzing Isosurface Visualization of Volume Datasets. IEEE Trans. Visual Comput. Graphics **20**(4), 513–522 (2014). https://doi.org/10.1109/TVCG.2014.20
95. Holzhüter, D., Pototzky, A., Hühne, C., Sinapius, M.: Automated Scarfing Process for Bonded Composite Repairs. In: Wiedemann, M., Sinapius, M. (eds.) Adaptive, Tolerant and Efficient Composite Structures, pp. 297– 307. Springer, Berlin, Heidelberg (2013). https://doi.org/10.1007/978-3-642-29190-6_23
96. Cantwell, W.J., Morton, J.: The significance of damage and defects and their detection in composite materials: A review. The Journal of Strain Analysis for Engineering Design **27**(1), 29–42 (1992). https://doi.org/10.1243/03093247V271029
97. Erlbacher, E., Lester, E., Godwin: Automated scarfing and surface finishing apparatus for complex contour composite structures. American Society of Mechanical Engineers, Manufacturing Engineering Division, MED **6** (2011)
98. Rodeck, R., Schueppstuhl, T.: Repair of composite structures with a novel human-machine system. In: Proceedings of ISR 2016: 47st International Symposium on Robotics, pp. 1– 7. VDE, Berlin, Germany (2016)
99. Kähler, F., Masekowsky, S., Schüppstuhl, T.: Automated Grinding for Surface Defect Removal on Aircraft Components (2023). https://doi.org/10.13140/RG.2.2.14302.61766
100. Hörstel, F., Kähler, F., Schüppstuhl, T.: AI evaluation of repair data in the aviation industry - Data-driven condition diagnosis of aircraft components. WT Werkstattstechnik **112**(9), 613–618 (2022)
101. Moenck, K., Laukotka, F., Deneke, C., Schüppstuhl, T., Krause, D., Nagel, T.: Towards an Intelligent Digital Cabin Twin to Support an Aircraft's Retrofit and Base Maintenance (SAE Paper 2022-01-0046) (2022). https://doi.org/10.4271/2022-01-0046
102. Laukotka, F.N., Krause, D.: Supporting Digital Twins for the Retrofit in Aviation by a Model-Driven Data Handling. Systems **11**(3), 142 (2023). https://doi.org/10.3390/systems11030142
103. Deneke, C., Moenck, K., Schueppstuhl, T.: Augmented Reality Based Data Improvement for the Planning of Aircraft Cabin Conversions. In: 2021 The 8th International Conference on Industrial Engineering and Applications(Europe), pp. 37– 45. ACM, Barcelona Spain (2021). https://doi.org/10.1145/3463858.3463896
104. Laukotka, F.N., Krause, D.: Virtual Representations of Physical Assets - a literature study about Digital Twins from the perspective of application in aviation's retrofit. Procedia CIRP **119**, 926–931 (2023). https://doi.org/10.1016/j.procir.2023.03.136
105. 3D-Printed 'Bionic' Parts Could Revolutionize Aerospace Design | GE News. https://www.ge.com/news/reports/3d-printed-bionic-parts-revolutionize-aerospace-design Accessed 06 Sep 2023
106. Aeroshark. https://www.lufthansa-technik.com/en/aeroshark Accessed 06 Sep 2023
107. Zutin, G.C., Barbosa, G.F., de Barros, P.C., Tiburtino, E.B., Kawano, F.L.F., Shiki, S.B.: Readiness levels of Industry 4.0 technologies applied to aircraft manufacturing — a review, challenges and trends. The International Journal of Advanced Manufacturing Technology **120**(1), 927–943 (2022). https://doi.org/10.1007/s00170-022-08769-1
108. European Commission. Directorate General for Research and Innovation., European Commission. Directorate General for Mobility and Transport.: Flightpath 2050: Europe's Vision for Aviation: Maintaining Global Leadership and Serving Society's Needs. Publications Office, LU (2011). https://data.europa.eu/doi/10.2777/50266 Accessed 07 Sep 2023

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