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CRITICAL REVIEW

Integrating X-reality and lean into end-of-life aircraft parts disassembly sequence planning: a critical review and research agenda

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Abstract

In parallel with the fast growth of the second-hand aviation market, the importance of promoting remanufacturing analytics has increased. However, end-of-life (EoL) aircraft parts remanufacturing operations are still underdeveloped. Disassembly, the most challenging and central activity in remanufacturing, directly affects the EoL product recovery's profitability and sustainability. Disassembly sequence planning (DSP) devises ordered and purposeful parting for all potentially recoverable components before physical separations. However, the complexities and uncertainties of the EoL conditions engender unpredictable DSP decision inputs. The EoL DSP needs emergent evidence of cost-effective solutions in view of Industry 4.0 (I4.0) implications and stakeholders' benefits. Among the I4.0 technologies, X-reality (XR) particularly hits the mainstream as a cognitive and visual tool consisting of virtual reality, augmented reality, and mixed reality. Recently, with the advance of I4.0 phenomenon, lean management has been theorized and tested through complementary collaboration. Since the research of integrating lean and XR into the EoL DSP is underexplored in literature, XR and lean are investigated as assistive enablers in the DSP. This study has a two-fold purpose: (1) identifying the key concepts of DSP, I4.0, XR, and lean, and extending the literature by reviewing the previous efforts of EoL aircraft remanufacturing, XR-assisted DSP, and XR–lean applications; (2) proposing "Smart Disassembly Sequence Planning (SDSP)" as a new EoL decision-support agenda after analyzing relational advantages and evolving adaptability. The barriers and limitations are highlighted from the recent associated topics, concrete academic information for developing digitalized disassembly analytics is provided, and new trends are added for future disassembly research.

Keywords End-of-life (EoL) aircraft · Industry 4.0 (I4.0) · Smart disassembly sequence planning (SDSP) · X-reality (XR) · Lean

1 Introduction

Sustainable management of the aviation industry requires planning treatment as an aircraft is approaching the end of its operational life. Since the 2010s, end-of-life (EoL) aircraft management has emerged as an established research area [1]. EoL aircraft management refers to the whole process planning of withdrawing, disassembling, and dismantling a soon-to-be-retired aircraft [2, 3]. As the research development of EoL aircraft management is still in the initial stage, some critical perspectives and guidelines have been provided in the representative publications of associations or companies associated with aircraft, such as the International Air Transport Association (IATA), International Civil Aviation Organization (ICAO), Airbus, and SGI Aviation. As IATA's 2018 workshop manual "Best Industry Practices for Aircraft Decommissioning (BIPAD)" indicated, the economic life of aircraft considerably influences the decommissioning decision (i.e., whether a used airplane should be removed from the fleet). It can be stated that a vast majority of airplanes were retired before the end of their technical lives. More precisely, the extra serviceable time they can extend was estimated to be at least 10 years [4]. According to "The ICAO Environmental Report 2019," the process for Advanced Management of End-of-Life Aircraft (PAMELA)—a well-established project by Airbus—proved that 85% of the aircraft (Airbus A300) content was recycled in 2005 [5]. Recently, it was determined that 90% of the used serviceable content of soon-to-be-retired

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aircraft could be recycled or reused [4]. Therefore, the mission of researching EoL aircraft management is worthwhile to support constantly.

Prior to the COVID-19 outbreak, Avolon's "World Fleet Forecast" predicted that approximately 13,000 planes would be scrapped by 2030, while Flightglobal estimated this figure to be 17,000 [6]. Since retired aircraft are not allowed to fly again, high-volume parking and storage demands can cause financial waste and environmental risks [4]. Uncertain external factors (e.g., financial crises, oil prices, and the pandemic) have already caused the number of decommissioned aircraft to fluctuate considerably [7]. Taking the present waste and unpredictable risks into account, improving the efficiency of treating incremental EoL aircraft is an urgent need [8].

According to the introduction of BIPAD, aircraft decommissioning practices can be organized into four sections: (1) the decision to decommission an aircraft, (2) the selection of facilities, (3) disassembly and dismantling processes, and (4) parts distribution and recertification [4, 5]. As the first and most challenging operation in the EoL stage, the disassembly process involves the systematic separation of all valuable components [9]. "EoL aircraft disassembly process" can be defined as the removal of valuable and potentially recoverable components from equipment or subsystems for aviation purposes (i.e., installing them in other in-service aircraft after authorized procedures). However, the complexities and uncertainties of EoL conditions (i.e., anticipated structural changes during the useful life) may cause disassembly to be an uneconomical process. For instance, a component damaged to a degree under various working ages may cause unpredictable operational failure. It is also unclear whether the component could be smoothly and directly removed. Faced with these issues, disassembly sequence planning (DSP) was prompted and released to foresee the task order and flexible adjustment details. DSP has been an object of research in the last three decades, but few studies have focused specifically on EoL aircraft [10]. Specially, an aged aircraft part is a high-value, high-precision, large-sized, and heavy technological product with substantial components that also exhibits varying conditions [11]. The highly complex EoL products with a multitude of components have increasingly revealed that traditional disassembly solutions are time-consuming and impractical. Because of the surge of Industry 4.0 (I4.0) technology research over the past decade, this trend has created the technological push factors for traditional manufacturing. If any assistive I4.0 technologies can facilitate decision-making processes, the desired competitive advantage will help DSP of EoL aircraft tackle the above-mentioned challenges.

In this paper, X-reality (XR) is an assumed technological enabler in the DSP decision-support system. Among the diverse I4.0 technologies, XR is a unique tool. This study agrees "X" as an attribute or preference variable, consisting of all relevant virtual-twinning technologies such as augmented reality (AR), virtual reality (VR), mixed reality (MR), diminished reality, and multi-mediated reality [12]. By applying XR, the virtual objects are created by rendering and programming a realistic simulation of the physical objects. Moreover, XR can offer agile human–computer interactions through the 3D position detection of hardware and virtual interfaces [13]. Since XR-related devices and software techniques are affordable, the fast-growing scientific attention on manufacturing systems has been accelerated further. The gradual implementation of XR has reported several advantageous applications in disassembly planning research, for instance, AR operational guidelines [14, 15] and VR vocational training [16]. XR has a broad application prospect, but collaborative XR applications are still missing in EoL DSP.

Apart from the technological enabler, an improvement-driven operational management approach is a key success factor for transcending traditional disassembly planning. Lean, a management approach originating from the production philosophy of "Toyota Production System" in the 1950s, has been applied across diverse and transdisciplinary engineering fields for decades [17]. Regardless of how varied the redefinition of lean has been, the primary objective of lean-based thinking is to eliminate waste and facilitate the maximization of service value for end customers [18]. Waste (or Japanese equivalent "MUDA") is conceived as the paramount role in lean [19]. There are eight types of waste mainly introduced over the last 30 years, which are (1) transportation, (2) inventory, (3) motion, (4) waiting, (5) overproduction, (6) over processing, (7) defects, and (8) human talent [19, 20]. Lean covers a set of techniques and principles for striving towards operational excellence in the customer-pull demand context [21]. Apart from the well-known just-in-time (JIT), waste elimination, and kaizen strategies, the widely used lean tools are represented by value stream mapping (VSM), 5S, poka-yoke, visual management (VM), standardized work, and kanban: JIT is a common inventory-driven model for balancing the supply and demand within operations; kaizen is a Japanese word that refers to continuous performance improvement; VSM is a tool for targeting the future state map after drawing the material and information flows of the current production line and reducing non-value added activities; VM represents the visualization of lean; and kanban, a sign board technique, is one of the VM tools for implementing the JIT strategy [22]. Under the name lean management, identifying and eliminating any non-value-adding activities by tools and practices are core competencies. The link between two manufacturing paradigms, I4.0 and lean, has provoked extensive discussion in academia [17]. However, the XR–lean collaboration remains unstudied: it is not fully clear how XR can contribute to the operational performance improvement associated with the existing lean practices for traditional disassembly planning; lean improvements that could be attained through XR adoption in DSP are still in the nascent stages.

To the best of our knowledge, there is no systematic review to address DSP, XR, and lean for EoL aircraft treatment. The objective of the present article is to fill this gap by reviewing the extant literature on the applications of XR (AR, VR, and MR) and lean, and providing a research agenda based on the state-of-the-art of XR–lean in DSP. The remainder of this paper is organized as follows: Section 2 discusses the formation and conceptualization of EoL aircraft, DSP, I4.0, XR, and lean one by one. Section 3 overviews the entire research methodology and introduces the literature search procedures. Section 4 presents the result analysis of the selected literature; it analyzes the retrieved literature by reviewing the relevant theories, product types, and assistive techniques and then formulates and narrows down a tailored EoL aircraft DSP through XR and lean gradually. To expand future research avenues, Section 5 defines and presents a detailed DSP-centered research agenda, especially for complex EoL products. The outline of the present study is graphically presented as a flowchart in Fig. 1.

2 Theoretical background

2.1 EoL aircraft management

2.1.1 High-value aviation-purpose parts

BIPAD concluded with a list of typical high-value parts (shown in Table 1). These potentially recoverable parts are defined by their market value, which is impacted by supply and demand. Moreover, both BIPAD and SGI Aviation's "Decommissioning Study" emphasized the primary priority value of the engine [4]. The engines are even more valuable than the entire retired aircraft in certain situations [4]. Apart from engines, the top high-value parts or subsystems listed by SGI Aviation are landing gears, auxiliary power units (APUs), electrical power, flight controls, and navigation systems [7]. Furthermore, IATA listed other high-value components, including avionics, environmental control systems (ECS), safety equipment, wheels, and brakes [4].

Table 1 The typical high-value parts listed in BIPAD (the source of information: [4])

Potentially recoverable high-value parts for aviation purposes
Engines
Auxiliary power units
Avionics
Flight control systems
Engine control systems and thrust reversers
Environmental control systems
Hydraulic systems
Landing gear
Safety equipment (e.g., slides)
Wheels and brakes
Pumps and electric motors

2.1.2 Key activities in EoL aircraft management

This study readjusts main decommissioning activities in various practice and delivery situations theoretically for the following discussions (shown in Fig. 2): (1) the decision to decommission an aircraft; (2) facility selection; (3) disassembly; (4) disassembled parts recovery, recertification, and distribution; (5) final dismantling; and (6) disposal and landfilling. To further clarify the level of decision and highlight the related topics within wider remanufacturing research, the aviation-purpose parts

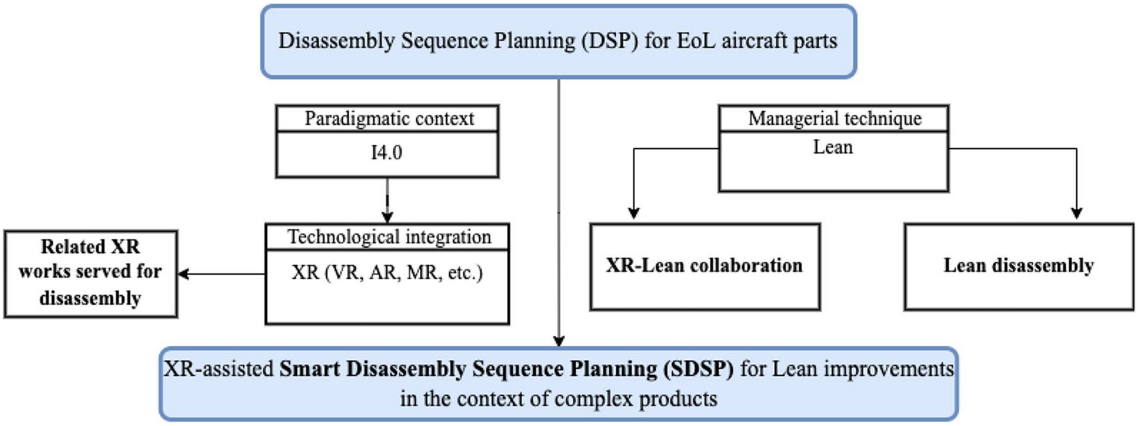
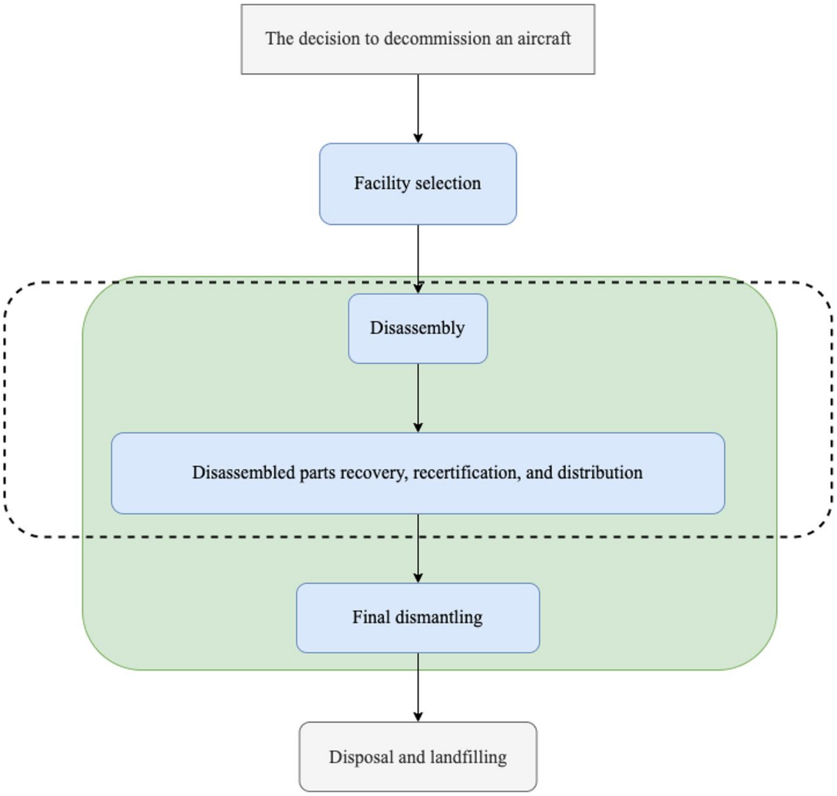


Fig. 1 The transitional information flows

Fig. 2 Key activities in EoL aircraft management (the source of information: [4])

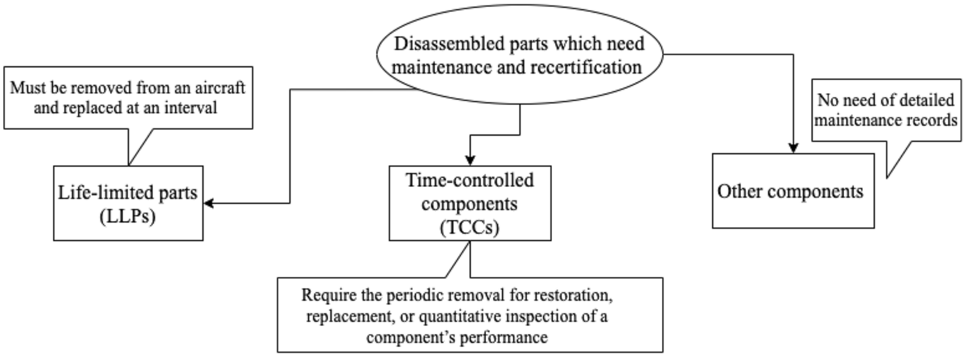


recovery work cluster (disassembly operations and disassembled parts' arrangements) is circled in the dashed black frame in Fig. 1 [23]. The general recovery and reuse procedures (disassembly and dismantling) are placed in the green zone.

Disassembly and disassembled parts Owing to the aviation-purpose character, disassembly is deemed "an aerospace activity" in the business context [4]. In the exploration of the additional features contained in the "disassembly" step, [4] concluded the following: (1) aircraft disassembly must be carried out by authorized aircraft maintenance organizations for maintaining the airworthiness of the disassembled parts, and (2) disassembled parts' information (e.g., historical status and current conditions) should be ensured and traced throughout the life cycle.

As presented in Fig. 3, [4] introduced and classified disassembled parts as follows: (1) life-limited parts (LLPs), (2) time-controlled components (TCCs), and (3) other components. Considering the value protections of LLPs, all record-keeping maintenance information is required. [24] added and addressed the importance of the modification-related information (e.g., ownership change and movement history) of disassembled parts. The value of each disassembled part is highly influenced by the actual supply and demand situations and the integrality of part information. The engine is a crucial factor in disassembly determination due to its stable value over time, which is mentioned in Section 2.1.1.

Fig. 3 The categories of disassembled parts (the source of information: [4])



Dismantling In contrast to disassembly, which focuses on component-level separation related to the management of spare parts, the “final dismantling” step involves material-level cutting and shredding of completely disassembled products [4, 23]. As presented in Fig. 4, dismantling refers to the processing that follows disassembly, and it deals with the remaining reusable parts and materials, except for aviation-purpose parts. Consequently, dismantling falls under the scope of “aerospace activity,” and dismantled materials will not be returned to the second-hand aircraft marketplace for trading and redelivering. Dismantling operations are not undertaken by any approved aircraft maintenance organizations. The remarketing paths mentioned by [4] (e.g., “art, gifts, furniture, trade show displays, movie sets/props, or for testing programs”) are the typical customized targets. While dismantled materials are less profitable than disassembled parts, the market value of recyclable materials could be extended or reconstructed because of specific characteristics [4]. Furthermore, dismantled materials are also required to be tracked and traced for reducing environmental damage. Aluminum recycling rates and removed material traceability highly influence the performance of the dismantling process [4].

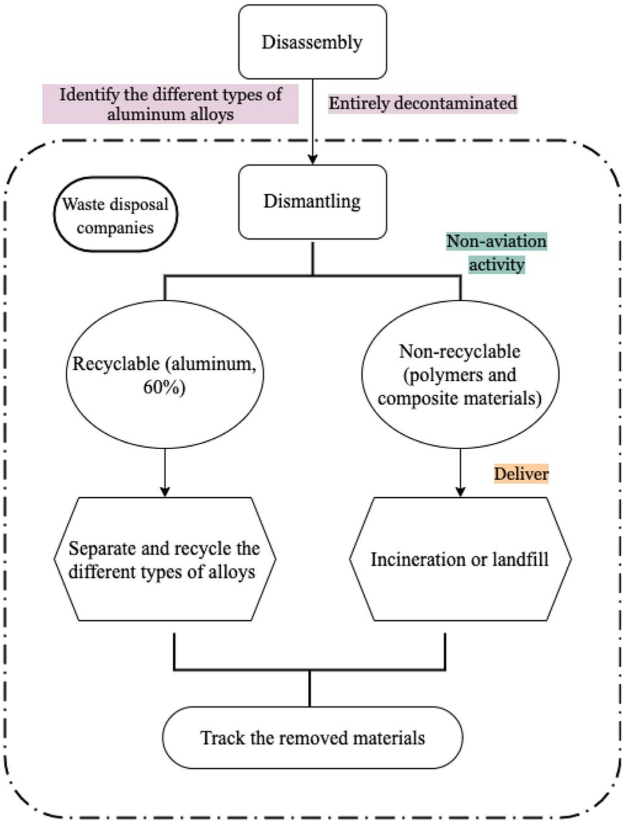


Fig. 4 The dismantling process (the source of information: [4])

2.2 DSP of complex products

Disassembly is a labor-intensive process in most application domains [25]. The “disassembly” step is a vital process for any EoL options or treatments [26, 27]; thus, this is the thematic research focus of this review. As a direction warranting deeper investigation within disassembly science [27], DSP outcomes are critical for the entire recycling chain network [9]. The primary objective of disassembly planning is to obtain sequential predictions in line with geometric or technical precedence constraints on subassemblies or components. In the literature on sequence-dependent disassembly planning, DSP is defined as a non-deterministic polynomial (NP)-complete problem [9]. The optimization of DSP would reach an organized and near-optimal sequence in terms of the feasible assessment factors and criteria. The most common optimization objectives encompass aspects such as disassembly cost, time, distance, removal directions, ergonomic performance, tool changes, and energy consumption. The optimization objective could be predefined at the starting point (e.g., consumer demand), and the function is typically intended to achieve the least disassembly costs and lead time overall. Furthermore, the objective function of disassembly must interact with uncertain, but crucial, external factors, such as disassembly rules, return yield, and insufficient information from historical documentation. According to the findings of [27–29], the general DSP solution spans three distinct steps: (1) disassembly process/type/level identification, (2) disassembly information modeling, and (3) sequence decision analytics.

Reference [30] defined the disassembly process/type/level identification as the “disassembly mode” selection. Similarly, [27] extracted partial disassembly sequencing topics while considering the categories of disassembly process/type/level identification. The operational target and customization split the disassembly processes into manual and robotic. The disassembly type can be classified into two groups: sequential disassembly and parallel disassembly. Sequential disassembly refers to a type of one-by-one removal, while parallel disassembly involves multiple removals at the same time. Thus, parallel disassembly could help more humans, and it could allow human–machine collaboration to gain noticeable advantages [27]. Moreover, to minimize the adverse effects on labor time, parallel disassembly planning methods could be utilized in large, complex EoL products [30]. The disassembly level entails full or partial disassembly according to various disassembly depths. Partial disassembly is generally implemented in maintenance procedures, while complete disassembly is often performed in the treatment of EoL products.

The second procedure, “disassembly information modelling,” supports the product topology and geometry information structuring geared toward a representation model [31].

Its mission is to help search for all feasible sequences. The reference could be a geometrical representation (e.g., CAD models) or a hierarchical list of subassemblies' profiles (e.g., bill of materials (BOM)). Three mainstream categories were reported in a recent review paper by [30], as presented in Table 2: (1) graphs, (2) Petri net, and (3) matrix.

The third procedure, "sequence decision analytics," is executed based on the EoL product representation because the capabilities of disassembly sequence searching are directly affected by it. This procedure would predefine and deploy solution approaches (e.g., mathematical programming, fuzzy, and simulation-based methods) to compare feasible sequential outcomes until a near-optimal route is obtained [11]. In the literature, the majority of the research has been conducted on the "information model + optimization algorithms," which can be described as the conventional solution [27]. However, the highly complex EoL products with exponentially growing components have increasingly revealed that traditional disassembly solutions are time-consuming and impractical. With the exception of the original equipment manufacturer (OEM), third-party service teams undertake the disassembly tasks independently [32]. When acquiring the limited information on the EoL product for the subsequent representation modeling, this information is not visible to facilitate the accurate navigation, detection, and display of all parts' connections, removability, and separability. Moreover, considering the stochastic nature of the disassembly process, one-fold mathematical programming cannot be a final settlement [27]. Hence, hybrid and heuristic methods assisted by emergent technologies have been encouraged to be applied for managing great numbers of subassembly groups. Computer-aided disassembly planning was proposed in the early stages and has evolved continuously over the last two decades [33, 34]. This directional motivation has been updated through the development of technological tools engendered by the evolving industrial revolution. For instance, technology-assisted push factors are interconnected with visual computing technologies' development, as they can regenerate visual imagery and foster detection for searching removable parts in a short period. However, the entire operational improvement response of EoL aircraft appears to be delayed compared to the growth of I4.0 technologies.

2.3 I4.0, XR, and lean

2.3.1 I4.0

I4.0 refers to the fourth industrial revolution and has been discussed frequently in recent research [35]. Since I4.0 is defined as an autonomous, flexible, and resilient data-driven commissioning paradigm, this technologically framed research stream has gradually transformed from a vague concept into potential service intelligence [36]. The tendency to apply information and communication technology (ICT) has already been embodied in practices that favor I4.0. The progress driven by computing power and software efficiency highlights the advances of I4.0 [37]. In *Green Supply Chain Management*, a book by [38], a solution involving green information and communication technologies (GrICT) was identified: GrICT systems could support operational, tactical, and strategic decision-making processes [38]. The available GrICT solutions comprised various I4.0 technologies. Moreover, GrICT aimed to "make ICT solutions for

Table 2 Disassembly information modeling methodologies for EoL product representation (the source of information: [30])

Category (formats)	Description
1- Graphs	*Targets:* (1) Disassembly process visualization (2) Inclusion of disassembly details (such as disassembly time and tool) *Representative methods:* (1) AND/OR graph (2) Hierarchical graph (3) Liaison graph (4) Contact state graph
2- Petri net	*Targets:* (1) Provide detailed descriptions of how the parts are connected (2) Simplify and generate the reachability graph effectively *Representative methods:* (1) Extended stochastic disassembly Petri net: arbitrary distribution (2) Fuzzy attributed and timed predicate/transition net (FATP/T), fuzzy reasoning Petri net (FRPN): uncertainty problems
3- Matrix	*Target:* (1) Minimal manual intervention *Representative methods:* (1) Disassembly interference matrix (2) Multi-direction matrix (3) Disassembly transition matrix

managing green practices" in most engineering fields. In the current I4.0 context, VR, AR, the internet of things (IoT), digital twin (DT), big data, cloud computing, cyber-physical systems (CPS), 3D printing, and robotics all represent mainstream technologies and systems [39]. In essence, the integration of hybrid I4.0 applications can offer real-time and high-assurance transactions for optimized decisions because these rely on data-orientation connectivity to enhance the involved capabilities in cyberspace. However, despite the growing number of academic works that have indicated the applicability of I4.0 technologies, the proven implications require demonstration. Essentially, the scholastic content of real-life I4.0 applications' evaluation and examination is minimal. The literature has shown that some relevant "4.0" terms have been created, such as "Disassembly 4.0" [40], "Aviation 4.0" [41], "Lean 4.0" [42], and "Remanufacturing 4.0" [43]; these are unlocked by the aspirational opportunities generated. The evolution of decision-making methods toward a smarter DSP is neglected in the majority of the extant literature, and the cooperation and functions of I4.0 technologies are rarely involved in the disassembly process [44]. As the adoption of I4.0 technologies has restricted adaptability challenges (e.g., unacquainted skills, information overload, and investment limitations), there is a need to investigate detailed I4.0 technologies for the DSP of EoL aircraft parts.

2.3.2 XR

XR represents a taxonomy of "realities" [45]. XR technology includes various sensitive sensors and abundant data-driven twinning techniques, generating high-fidelity objects or scenarios [13]. The generation of stereo images, sounds, animations, and sensations, made possible by compatible game engines (e.g., Unity3D and Unreal), is entirely virtual [46]. For example, in a VR-based environment, users can enter and move in the virtual world with a first-person view and a "sense of presence," while feeling spatially realistic [47]. The user can wear interactive devices (e.g., head-mounted device (HMD) and hand-held display (HHD)) to view the twinning objects in the virtual environment and use multi-sensory tracked controllers to experience the programmed activities with low-latency motions [48]. AR is another representative XR technology, and its virtual 3D objects are merged with real surroundings, which enables the user to see the overlapped reality [49]. The output elements made by AR are observed in the real world. As opposed to VR, the objective of AR application development is not immersive, and AR's capability may rely on the real environment. MR is a collective term or vision based on virtuality and reality blending research, and it covers various levels of reality and immersion [50, 51]. Regarding the notion of the "reality–virtuality continuum" agreed upon by several researchers, MR has been placed on the continuum from completely physical environments to computer-generated immersive ones [52–54]. Essentially, AR belongs to the MR continuum, and MR has been described as remote collaborative technology that also contains AR. Therefore, MR is an alternative concept that can assist in the correction process of AR-related work. The general four-zone cluster of virtuality and reality is illustrated in Fig. 5.

The relevant academic communities and high-tech companies have already shaped XR to become more stable and mature in many application domains. Its widespread implementation has been active in several fields, including engineering education [55], interactive video games and playable media [56], architecture and construction [57], aerospace [58, 59], marine studies [60], and medicine [61]. Built on the swift development of continuously upgraded software and ergonomic hardware, XR is not limited to characters as a visualization tool or display technology [62–64]. Grounded in a human-centric mindset, VR is a countermeasure because the artificial virtual environment can create dangerous job-shop scenes for training operators [65]. Since VR can engender more intuitive interactions between the operators and the immersive environment, the enlightenment process can be accelerated. In addition to the training, VR can help simulate the operational workplace with respect to ergonomics and productivity. For instance, [66] applied VR to simulate new assembly scenarios for the cabin and cargo of an aircraft. The assembly processes were planned and evaluated beforehand through the VR simulator, and dispensable costs and time could be reduced before the

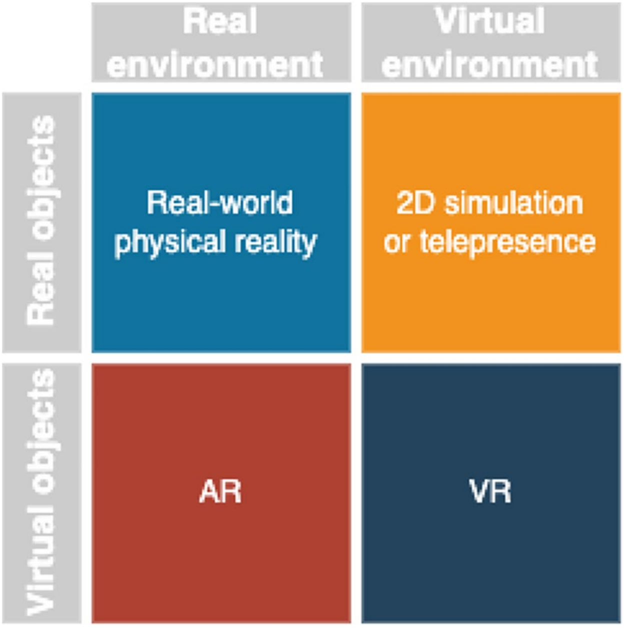


Fig. 5 The general classification based on the objects and the environment

physical systems were accessible. Moreover, motion capture systems can be incorporated into VR experimental scenarios. In their experiments, a real-time ergonomics analysis could be implemented as the motion data was captured. The avatar they presented, which represents a 3D anthropomorphic digital representation of the worker, was examined by the external supervisor regarding the movements and postures. Similarly, [67] also integrated VR and motion capture systems to design the assembly system workplace, considering productivity and ergonomics. The distinction was that they focused on reducing the physical capabilities of the aging workforce during the workplace design period. In the study of [68], representative postures for disassembly tasks embrace standing, bending, and kneeling for the helicopter and aircraft. Traditional disassembly can also gain the chance to improve the well-being and security of workers through ergonomic assessment in virtual environments. The proven industrial contributions of AR are about spatial positioning and gesture recognition of multi-modal information [65]. For instance, [69] designed two AR user interfaces for remote services and guidance systems during maintenance management practices. Moreover, their designs also recognized the needs of the aging workforce and put them as the first step of prototyping processes. The uptake of XR can help promote the connection between human and avatar.

To extend and augment the experiential perception and understanding of operators, cognitive ergonomics should also be considered in addition to physical ergonomics. The cognitive and emotional resources of an individual operator can be measured for the fundamental human elements in addition to the muscular resource. Notably, a significant portion of the publications have focused on the ergonomic perspectives relevant to human cognitive and visual behavior in both AR and VR environments [70]. However, so far, it is inevitable that a single AR, VR, or MR hardware or software can only partially satisfy the requirements of the real-life environment because of their technical limitations [71]. “Cybersickness” has been a marked drawback since the adoption of XR became a possibility [70]. As the wearable equipment (HMD and other body-tracking sensors) is a required aid, the technical constraint of unstable resolution displays currently coexists with the rapidly increasing fidelity [72]. Through a partial field-of-view (FOV), VR scenarios are devised to simulate an immersive environment to facilitate a better physical and mental user experience. The allowed movements of hands, heads, or legs interact with the sensors of input devices. However, apart from possible negative experiences, some cybersickness problems are caused by long-time virtual environments—for instance, oculomotor issues [73]. The weights of HMDs, glasses, and other relatively clumsy devices can also cause experiential distraction [72]. While industrial XR has a broad application prospect, its real-life deployment for EoL aircraft parts is still a challenge because its practical exploration remains insufficient. XR applications’ specifications should be developed and examined based on the field requirements [46].

2.3.3 Lean

To outpace global competition, conventional manual disassembly processes require effective management practices such as lean methods. Lean management has its roots in manufacturing management, and integrative lean thinking is a potentially natural guideline that can prove useful for sustainable production planning [74]. From the operations point of view, lean management is particularly relevant for removing of non-value-adding operational practices to enhance natural resource efficiency [75]. Although energy consumption and emissions are not traditionally included in the waste types within the lean domain, environmental performance has gradually become a concern in lean improvements [74, 75]. Previous studies have investigated the adoption intention of lean in circular practices and sustainable manufacturing [74–77]. Given the dominance of lean, lean remanufacturing has recently gained incremental attention in academic research [76, 78], with lean disassembly distinguishing itself under the term “Lean Remanufacturing.” While the present study does not review the impact of lean on environmental potentials and drawbacks, integrating lean into disassembly planning aligns with the trend of the emergent literature on lean and sustainability. As a methodical paradigm-shifting standpoint, the aim of lean disassembly is to increase predictability and productivity in an organized manner with a set of lean tools and principles. As a more focused research topic, lean DSP enables a functional understanding of disassembly planning and sequencing. In line with the objectives of DSP, the identification and elimination of waste (such as time and steps) can play a vital role in reducing disassembly operation costs and lead time. Moreover, the value stream of DSP can serve as a fundamental approach to map process-scoping information and incorporate customer preferences into the improvement process. Despite the unresolved issues within the lean disassembly community, lean DSP can offer actionable spaces that can help analyze the role of lean.

Since the I4.0 phenomenon has been established, the innovative adoption of emergent technologies is anticipated for the continuous improvement of operational effectiveness [79]. The deployment of I4.0 technologies is expected to bring favorable impacts through purposeful fulfillment of transformational digitalization, enabling smart manufacturing and smart decision-making [80]. However, despite the recent maturity of I4.0 technologies, remanufacturers still lack a comprehensive understanding of how I4.0 technologies can affect the established lean disassembly. Previous literature has constantly argued that lean has evolved to coexist with information-driven technologies [22], and lean and I4.0 are interconnected due to their commonalities in operational performance [81]. Recent studies have focused on two directional perspectives: lean is the basis of I4.0, or I4.0 improves the effectiveness of lean operations [17]. The lean-I4.0 transformation is intended to create high impact and immediate value during product-process management. The integration of concrete I4.0 technology, such as XR, can be closer to the practical needs of lean operations. However, there are relatively few accounts in the academic literature relating to the XR–lean corporation and its implications. Overall, the convergence of existing managerial techniques and industrial XR remains nascent. XR applications offer inspirational opportunities but also engender new managerial obstacles to achieve lean targets. To demonstrate the viability of I4.0-driven and XR-integrated disassembly planning, there is a need to adapt to the current state of industrial environments. The gap concerns two points: (1) whether XR can support the lean-oriented decision-making process to avoid the excessive use in terms of integration and investment [82]; (2) how industrial XR can leverage its capabilities (e.g., multidimensional information-sharing and visualization) to enable a lean disassembly system [79].

In addition to the practical advice on the process for improving productivity, the workforces behind the tools are crucial factors for successful lean implementation [83]. Customization needs and expectations are the first steps to identify when implementing the lean strategy, but possible contradictions exist among efficiency, waste, customer benefits, and workforce satisfaction. To enhance the value of lean principles, the primary focus on productivity, resources, and customer benefits represents its social and economic objectives. However, business pressures and competitive environments have influenced the decision-making attitude of managers, as well as morale and workload of each worker. In the extant literature, human-centric issues were particularly relevant to organizational development as the external and internal pressures could be exposed by lean [83]. When the occupational health and safety responsibility is addressed at scale, physical and psychological human aspects of employees are accumulated issues [83]. To recapture the value of the workforce, previous scholars (e.g., [84] and [85]) indicated that lean could be evolved as an integrated socio-technical working system. To meet human-relevant objectives, enhancing the "smartness" of the product-process improvement can be a positive manner in response to varying external conditions. The deployment of community and inclusion can be revisited and adjusted through the potentialities of integrative emergent technologies.

The initial definitions of EoL aircraft parts, DSP, I4.0, XR, and lean have been introduced one by one. To cope with aforementioned gaps, it is necessary to review the relevant XR-assisted applications and potential XR–lean collaboration methods in this research plan. Furthermore, specific attention is given to the original vision of perspectives and challenges for disseminating the XR–lean application to disassembly science. This paper aims to explore the following three research questions (RQs):

RQ1: What is the state of the existing I4.0-driven EoL aircraft recovery management research? How did XR technologies impact DSP development?
RQ2: Which enabling features and expected functionalities should be included in XR–lean DSP for EoL aircraft parts?
RQ3: What future research agenda is presented for XR–lean DSP?

3 Research approach and descriptive analysis

This review is intended to be inductive and comprehensive to answer RQs and refine theory-driven derivation for a potential enabler, XR-lean collaboration, as a built-in characteristic of a new DSP-centric agenda. Based on three RQs, this section explains the search strategy, detailed screening, selection, and extraction processes of this review-based paper. As a transdisciplinary research topic, this review is related to the application domains of computer-integrated remanufacturing, operations management, and computational media design.

To provide structured content in the co-located DSP, XR, and lean literature, two well-known databases, Web of Science (WoS) Core Collection and Elsevier Science Direct (SD), were used, thus covering multidisciplinary domains for this discourse. These two databases have varying advantageous features and executive filter interfaces. The breadth of coverage might be one of the most important comparative components. To summarize and capture the current state of research, WoS and SD were applied to perform the literature search on a case-by-case basis; they yielded two different numbers of samples associated with two distinct proposed views: initial view and network view. WoS was the first avenue for obtaining initial descriptive findings of the extant research, and this could be identified as a macro-level pre-analysis phase. The expected records could be relatively higher. SD was the second avenue for configuring the knowledge areas of the content analysis. A logical screening employment was the intended objective of using the SD database. This two-step (two-view) method was devised to reduce the steps for the inclusion and exclusion criteria repeatedly. It addressed the synthesis and categorization of selected publications in an identical topic scope. Moreover, it was an attempt to explore the dimensions and sub-dimensions of potential XR–lean DSP application areas. Both the breadth and depth of the literature on XR–lean disassembly planning were taken into consideration.

In addition to the basic inclusion criteria (i.e., English-written, peer-reviewed, and full-text publications) in this review paper, the collective decisions of the search strategy were determined as follows:

- Temporary scope: this review was finalized in October 2022. To provide our findings for examining the joint applicability of XR and lean in the state-of-the-art coverage, materials published up to 2023 were chosen. Therefore, in-press publications could be covered because they would be published in 2023, even though 2022 is not yet over. Moreover, the principal articles were restricted to those published after "Industry 4.0" (German equivalent "Industrie 4.0"), which was profiled in 2011 [79]. Consequently, the identified publications were published between 2011 and 2023.
- The present analysis focuses on industrial engineering. Therefore, the research area selection of WoS and SD was specified to search, for instance, the "Management Sciences" area filter in the WoS and "Decision Sciences" subject area filter in the SD.

3.1 Initial view

Owing to the multidisciplinary search requirements, the WoS database was used in this phase, and the initial findings provided an early theoretical consideration of the topics. The objective was to outline the development trend of the XR–lean disassembly research community. As the key research objective is already illustrated in Section 2, the components that were contained in the body of the text should include "disassembly," "remanufacturing," "virtual reality," "augmented reality," "mixed reality," and "Lean." Therefore, the following search query was applied in the WoS database:

("remanufactur*" OR "disassembl*") AND ("virtual reality" OR "augmented reality" OR "mixed reality" OR "Lean")

In accordance with the aforementioned inclusion criteria, Fig. 6 shows the pipeline of the first-stage screening strategy employed in WoS; a total of 1655 journal articles were listed.

The publication year and journal distribution charts are illustrated in Figs. 7 and 8, respectively. While Fig. 7 does not show the entire year-on-year growth, the publication dates of this related research indicate the attention it received in the literature. Amid the time frame years for the 12-year period of 2011–2023 (apart from the early access for 2023), the biggest cluster appears in the years between 2019 and 2022, and the second cluster indicates that many of the articles were published between 2015 and 2018. Overall, a growing body of research has tackled XR- or lean-related remanufacturing since 2018. Moreover, this trend could display the positive adoption development and increasing implementation patterns of XR technologies in related lean remanufacturing or disassembly areas after being

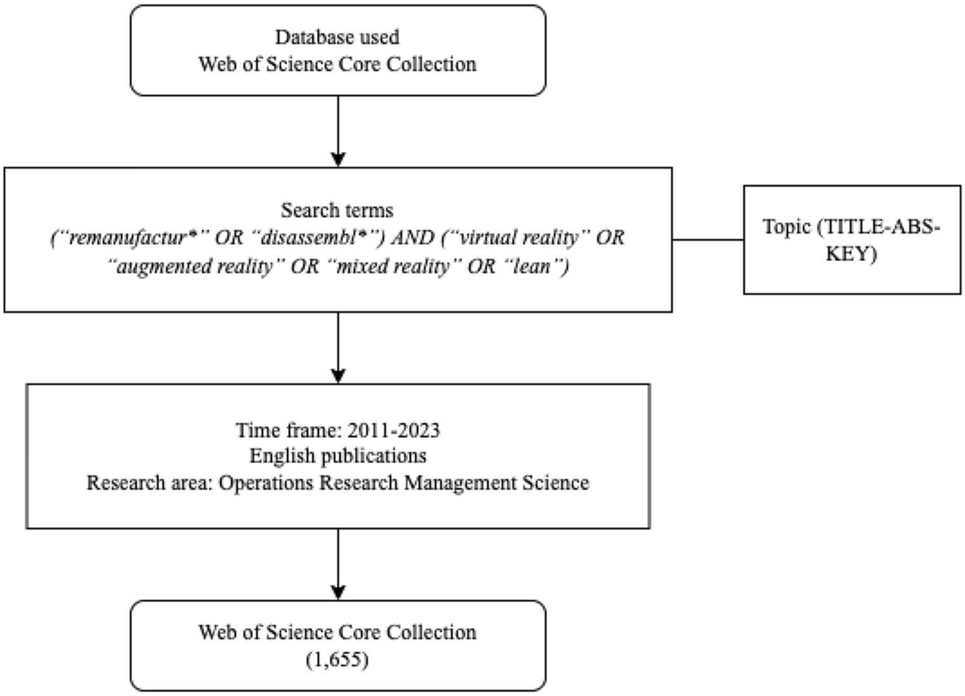


Fig. 6 The pipeline of the screening strategy for the WoS database

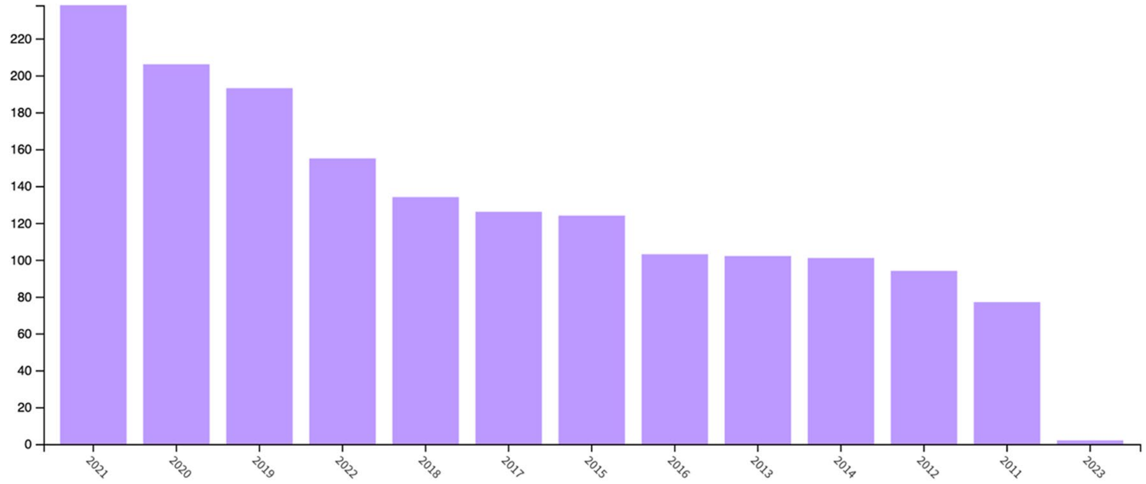


Fig. 7 Distribution of relevant articles by year of publication

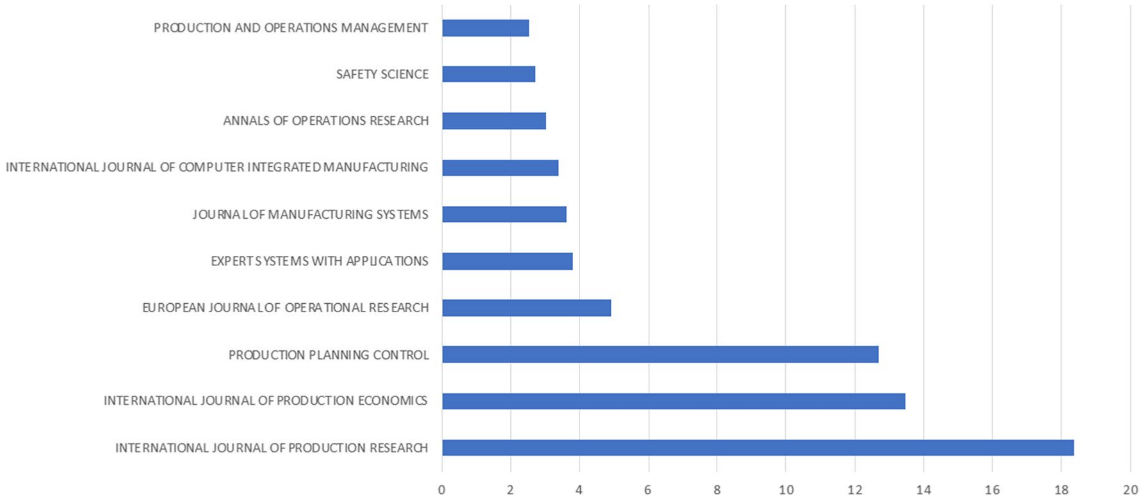


Fig. 8 Distribution of relevant articles by journal outlet

inspired by I4.0. As shown in Fig. 8, the top ten journals were extracted to analyze the publishing distribution: the existing articles were mainly published in the *International Journal of Production Research* (18.369%), *International Journal of Production Economics* (13.474%), *Production Planning Control* (12.689%), and *European Journal of Operational Research* (4.894%). Therefore, the dominant journals for XR–lean disassembly research were relatively intensive and shared nearly half of the whole ranges. *Expert Systems with Applications*, *Journal of Manufacturing Systems*, *International Journal of Computer Integrated Manufacturing*, and *Annals of Operations Research* contained 3.807%, 3.625%, 3.384%, and 3.021% of the articles, respectively.

3.2 Network view

Managing a diverse range of studies for examining scientific literature is the task of this stage [86]. After disseminating the descriptive trend and directional stream of XR–lean remanufacturing, the XR-infused and lean-guided disassembly treatments should be concerned with more evidence worthy of continuous research. The potential value of developing XR–lean applications in disassembly should be acknowledged by the limited literature, which exhibits unclear characterizations and a narrow scope among partially relevant applications. Furthermore, prior to unpacking and unfolding the detailed content analysis in the next section, an antecedent and consecutive arrangement of the detailed sample should be established in line with the topic features. A recent work, [87], applied a "network view" to enhance the completeness of the dimensions of literature analysis. This network view concerned the roles of enablers, and it was perceived as a combined perspective in which integration and coordination were set as the central themes.

In this stage, the search engine SD was used to find the final revision documents. Notably, the related XR–lean literature is extremely broad in accordance with the initial description findings. In addition to the synthesis of the relevant research articles, the breadth of research on the subject should be predefined through the categorization of extant publications. To ensure thoroughness in the following content review and to enhance the awareness of reviewing application-level gaps for DSP, a boundary network strategy informed the entire process in this stage. Furthermore, due to the real-life applications of I4.0 technologies (especially for EoL DSP) being nascent in the extant literature, the probationary combinations of these emergent terms had to be queried purposefully and studied manually. Regarding this, the main challenge was the isolation of distinct research points in the previous studies. Hence, their co-existence for mutual goals was addressed in this stage, and a specific search strategy was designed. To avoid drawbacks and comprehensively validate this study's assumption, a theoretical derivation approach was used for the publication selection; this is described below:

3.2.1 Identification and clusters of keywords

While the WoS database offered comprehensive coverage, all keywords had to be reclarified before these could be inputted into the SD search engine. The search term group segmenting method was inspired by two recent review papers: [88] and [89]. Based on their critical reviews, these two papers designed and developed I4.0-oriented agendas "Logistics 4.0" and "Assembly Systems 4.0," respectively. Both sets of the authors separated their defined keywords into two main groups: topic-related keywords and I4.0-related keywords. Following this, they processed the literature search based on the Boolean combinations of the two groups' content, which were displayed as the string "(keyword A among the group A) AND (keyword A among the group B OR keyword B among the group B)." In the present study, this method was slightly modified to obtain four groups for the initial findings on the assumed four-dimension integrations with conceptual boundaries: group A—component level; group B—operational level; group C—technological level; and group D—process (managerial) level. Groups A and B focus on the research object, while groups C and D focus on the targeted XR–lean assistance. As shown in Table 3, all the key concepts of this study were segmented and listed as four groups. To minimize the subjectivity, the considerations of the final retrieved samples focused exclusively on three themes: "EoL aircraft parts DSP," "XR-based disassembly," and "correlations and interconnections between XR and Lean." To avoid irrelevant literature searches, the final Boolean combinations were designed to experiment with the intention of low repeatability.

Table 3 Search terms in the four groups

Category	Selected terms
Group A—component level	• End-of-life aircraft • Aircraft parts
Group B—operational level	• Disassembly
Group C—technological level (emerging research frontiers)	• Industry 4.0 • Augmented reality • Virtual reality • Mixed reality
Group D—process level	• Lean

3.2.2 Literature search, screening, and eligibility checks

Table 4 presents the inclusion and exclusion criteria for preparing the next literature search and screening processes. To ensure accurate text mining for the analysis of the existing practical frameworks, methods, and applications, the relevant publications included in this stage consisted of journal articles, conference papers, and book chapters. To remove the excluded records, "Engineering," "Decision Sciences," and "Computer Science" were selected as the targeted subject areas while considering the mentioned search strategy. Therefore, other areas (e.g., "Material Sciences" and "Energy") were removed from the search filters.

Table 4 Inclusion and exclusion criteria

Inclusion and exclusion criteria	Description
Inclusion criteria	Publication time frame: 2011–2023 Type: • Peer-reviewed journal articles • Conference papers • Book chapters Selected subject areas (for searching X-reality and lean): • Engineering • Decision sciences • Computer science
Exclusion criteria	- No full text - Non-English - Non-peer-reviewed literature - Fields in material sciences, chemistry, biology, etc

In contrast to the initial view, this stage mainly aimed to provide supplementary details and maintain the extracted publications at a manageable amount. As shown in Table 5, the entire search process involved two steps: in the first step, based on the four groups' representations listed in Section 3.2.1, all the "keyword" groups were combined, and the high numbers of search results (shaded in grey) were abandoned and regrouped for the screening and refinement that followed. In the second step, the new combinations were built as alternative terms to be inputted for the corresponding adjustments. The second step yielded a more visible and readable realignment representation of the search terms. This searching view helped yield more justifiable results with higher relevance and accuracy. For instance, a search of the keyword combinations from groups B and C was performed: {"Industry 4.0" AND "disassembly"}. However, 353 results were obtained after considering the inclusion and exclusion criteria. Hence, this search query was replaced with a more focused alternative in the next step: {"Augmented reality" AND "virtual reality" AND "mixed reality" AND "disassembly"}. The number of retrieved publications in the SD engine was only 56. To match the research scope and RQs seamlessly, the quality and rationality of the selected publications were revealed through the total amount and repeatability in the final step.

The flowchart revealing the keyword combinations' search steps is presented in Fig. 9. A total of 194 relevant

Table 5 Two-step literature screening

Step	Group combinations	Search	Publications retrieved in Scopus
First step	A AND B	"End of life aircraft" AND "disassembly"	15
	A AND C	"Aircraft parts" AND "Industry 4.0"	32
	B AND C	"Industry 4.0" AND "disassembly"	353
	B AND C AND D	"Industry 4.0" AND "Lean" AND "disassembly"	114
Second step	B AND C	"Augmented reality" AND "virtual reality" AND "mixed reality" AND "disassembly"	56
	C AND D	"Augmented reality" AND "virtual reality" AND "mixed reality" AND "Lean"	64
	B AND C AND D	"Augmented reality OR AR" AND "virtual reality OR VR" AND "mixed reality OR MR" AND Lean AND disassembly	27

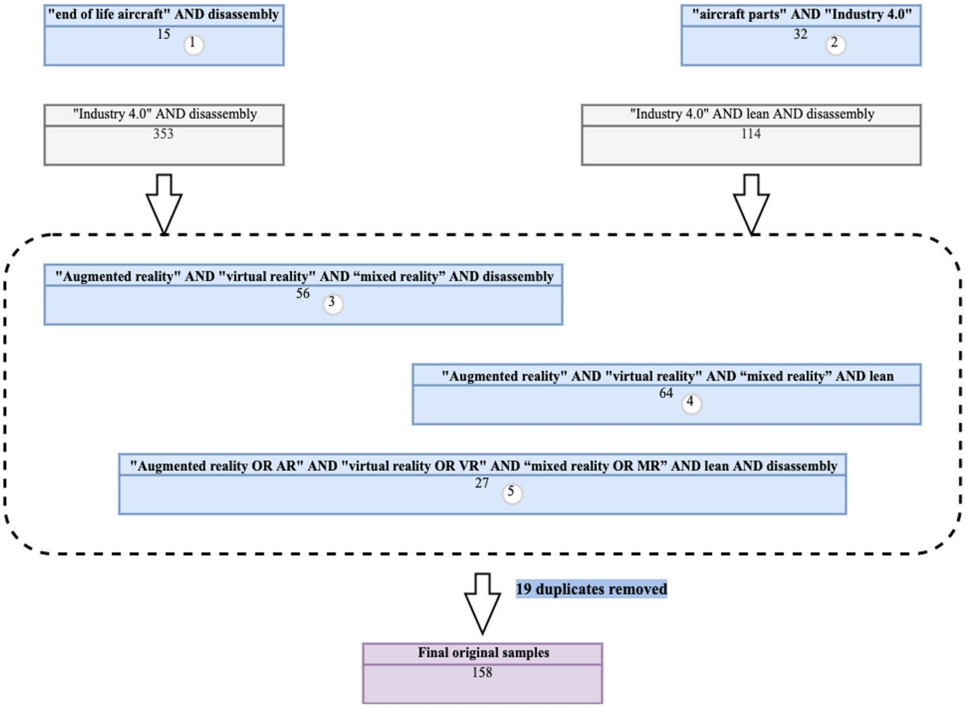


Fig. 9 Flowchart of the process of the literature search and selection

publications were retrieved via these two steps. Following this, Mendeley Reference Manager was used to check all the duplicates manually and removed an additional 19 results. Therefore, 175 final samples were obtained for the subsequent network and content analysis. The final round involved full-text screening. Notably, this search strategy is relatively concise and efficient.

3.2.3 Bibliometric visualization analysis

Basic statistics were not sufficient for a holistic descriptive analysis. The bibliometric aggregation and visualization of the extracted literature from SD were analyzed using VOSviewer (version 1.6.18). VOSviewer is a supportive software that helps coordinate the holistic vision of the research network and the representative distributions of various fields [90]. It can provide three visualized mapping types. Furthermore, this bibliometric visualization tool can help specify focused research trends and specify the research scopes during the systematic review process [91]. With regard to the search strings in Section 2.2.2, the manual recombination of keywords or terms lacked the directional analysis content of the existing works. By utilizing the VOSviewer software, the development distributions of the extracted literature were graphically illustrated. Moreover, the technological and knowledgeable applicability studied in the published works were revealed. The "supply and demand" of the selected research was made more visible—for example, the most relative research field that applied XR technologies. Furthermore, this analysis could provide broader insights for the conceptualization of future research avenues in the final discussion.

This section first presents the high co-occurrence keywords' network of the selected literature. Its node-link network map programmed by VOSviewer is displayed in Fig. 10. The nodes below represent keywords from hotspots of XR–lean DSP in the selected literature that were captured during the 2011–2023 period, such as AR, MR, and I4.0. Given the visual information, AR evolved into a particular technological dimension with a substantial growth in previous studies. Moreover, the various nodes' sizes, colors, and link widths are also comparable factors: these indicate the topics' or keywords' co-occurrence frequencies, the response clusters examined by VOSviewer, and the strength of pairs of topic areas or keywords, respectively [90, 91]. In Fig. 10, the occurrence numbers of the overall keywords' frequencies are set as five, and ultimately, there are 24 highlighted keywords (nodes) among the scientific literature topic areas.

Based on the five clusters formed in five different colors (red, green, blue, yellow, and purple) in the bibliographic coupling image, the co-occurrence of author keywords was determined via VOSviewer; this is shown in Table 6. The keywords were organized and examined using VOSviewer, and the featured function understanding could be less obfuscated in the literature.

Table 6 could reveal the obtained pictorial representation of the domains in the previous studies. Accordingly, the most researched domain of this topic area was the architecture engineering and construction (AEC) industry. "Construction," "building information modeling," and "Construction 4.0" were engaged in distinct clusters (different co-occurrence). While the basic descriptive analysis of the network visualization is limited, these directional outcomes could indicate that the increasing usage of XR was involved in the trend concerning the adoption of emergent technologies in the AEC industry. These emerging research streams could prompt the discovery of commonalities with the relevant DSP in the existing scholarly content. The technical and strategic issues with the omnipresent discussions on sustainability and digitalization are potential research sources.

Fig. 10 Overlay visualization map of the co-occurrence network of the selected literature

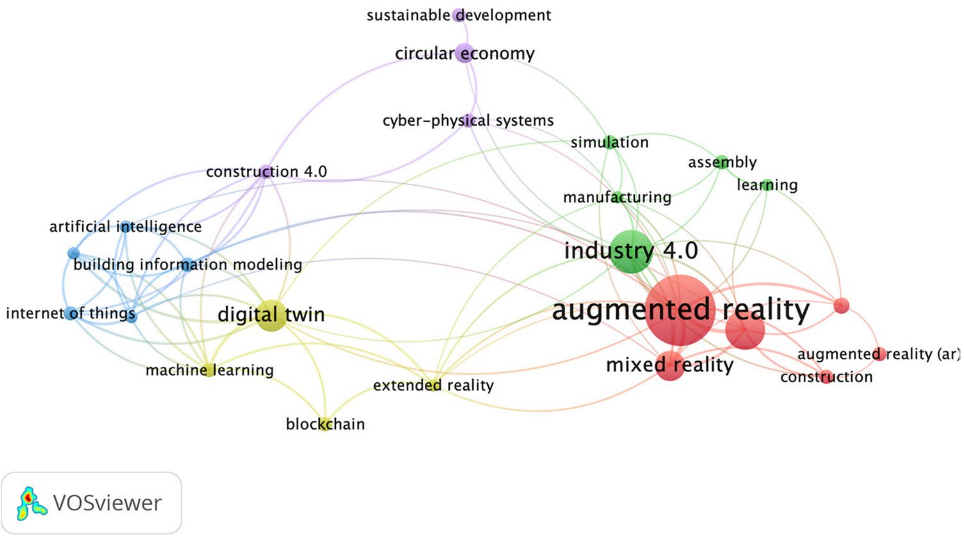


Table 6 The co-occurrence of keywords

No	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
1	Augmented reality	Assembly	Artificial intelligence	Blockchain	Circular economy
2	AR	Industry 4.0	Big data	Digital twin	Construction 4.0
3	Construction	Learning	Building information modeling	Extended reality	Cyber-physical system
4	Maintenance	Manufacturing	Edge computing	Machine learning	Sustainable development
5	Mixed reality	Simulation	Internet of things		
6	Virtual reality				

Moreover, XR might be the most promising technology in the pre- and post-manufacturing phases since the following shared aspects, “maintenance,” “assembly,” “manufacturing,” and “circular economy,” were formed in clusters. These evident fundamental overlaps could help the DSP content review to be more accessible and accurate. “Lean” is not present in Fig. 10. As XR and other I4.0 technologies were disclosed as key instruments, the transformative capacity of lean might be mitigated and counteracted at the technical level gradually. However, the managerial perspective of lean is still often criticized.

4 Review and content analysis

This review is intended to understand XR–lean DSP as a practical method at the technological and managerial levels. While there was an attempt to establish and reconceptualize the managerial and technological combinations during the publication selection and descriptive analysis processes, the fragmented and nascent statuses of understanding these infusion initiatives remain. Responding to this novel phenomenon and considering XR technologies as core instruments, the reporting and dissemination of this study were classified into three parts: (1) a sharp focus on the DSP for EoL aircraft, (2) the first-level infusion: XR-assisted DSP, and (3) the second-level infusion: XR–lean DSP. To merge and integrate XR technologies and lean naturally, this fast-track thematical structure could provide a starting point for the critical content analysis and the forecasting of emerging research areas presented below.

4.1 DSP in the context of EoL aircraft

Because of the issues generated by the high-volume data for EoL aircraft representation, [92] recommended, with a demonstration of the same, that the mathematical modeling of an EoL aircraft and its subsystems could utilize the *Aircraft Maintenance Manual* (AMM) as the only data source. In accordance with maintenance procedures, the disassembly operations were required to respect this for the preparation of the task graph [92]. The AMM may be a reliable alternative in certain situations, but the absence of representation information and the loss of components are the actual issues.

For DSP, [93] defined the EoL airframe “disassembly alternatives” and tested these on a real jet. They introduced the selection strategies for four “disassembly alternatives” that consisted of cutting, drilling operations, and manual disassembly operations [93]. However, this arrangement could be close to the dismantling stage (see Section 2.1.2.3) because they concerned material-level separations (cutting and drilling) more, such as the material types and different substances’ amounts. Notably, they also discussed the connections among the parts or modules and designed the feasibility analysis method based on the disassembly difficulty [93]. Afterward, the “disassembly factsheet” was made from operational information (e.g., operational time and number of fasteners) for the final evaluation. Similarly, [94] focused on the disassemblability index assessment, even though it was involved in the design phase. EoL disassembly planning must handle its own parameters as a dynamic activity, though maintenance is an indispensable reference. Furthermore, the component-level or product-level structural disassembly should be particularly emphasized.

Recently, [95] designed a quantitative disassembly planning model to evaluate the disassembly performance through a technical–economic score-based system. Their multi-variable disassembly evaluator analysis and the disassembly scenario selection (i.e., the formation of structural knowledge and database) were examined through the case of a mid-range airliner stabilizer [95]. This linear disassembly evaluator primarily concerned the difficulty of discovering parameters, time spent, and material compatibility. Despite the alloy element recovery aspect being a key factor, the stage should be described as post-disassembly planning that centers on dismantling. Nevertheless, the recommendations extracted from this paper inspired the disassembly science research for EoL aircraft parts. For instance, unlike the AMM, the information sources introduced by [95] comprised three categories: (1) primary sources: any data sheets or illustrations; (2) expert data: the observations and recommendations offered by specialists; and (3) machine data: the data obtained from visual techniques with the aim of non-destructive testing. Accordingly, the demand associated with advanced digital technologies and well-established decision-making methods for achieving operational excellence was explored intensively.

Regarding the rising popularity of "Aviation 4.0," [41] presented this I4.0-oriented revolution and defined its characteristics as intelligent applications in the cyber zone. For aerial maintenance processes, the Aviation 4.0 technologies demonstrated by the authors included AR and 3D printing [41]. This content was mentioned in a new book, *Intelligent and Fuzzy Techniques in Aviation 4.0*, by [96], and several representative chapters may be insightful, especially for the disassembly research community—for instance, the perspective exploration of fuzzy systems and AR application by [11]. As the scope of the present review covered such book chapters, the related decommissioning–disassembly content of this book was considered in the next-step paradigmatic facilitator.

Table 7 lists the summary of the disassembly treatment for EoL aircraft. The collaboration between computational intelligence and scientific management is nearly absent, and the same can be said for radical improvement in flexibility and efficiency. With I4.0 initiatives, there has been a considerable focus on technology-driven disassembly planning, originating from the aforementioned "computer-aided disassembly planning" [33]. A new "computer-aided disassembly planning" should be advanced with the aid of cyber-physical human–machine collaboration.

4.2 The first phase of the integrative infusion antecedents: XR-assisted DSP

To retrace the local XR-assisted DSP for the aircraft parts at EoL, the relevant AR, VR, and MR applications' collections were reviewed. The final sample results revealed that few researchers have considered the integration of XR into the EoL DSP system. While XR was not reviewed using a cross-application approach, the final samples reported that XR-related maintenance and assembly applications comprised a considerable portion of selected literature [71]. As the disassembly activity could not be avoided in maintenance and remanufacturing operations, and the current XR applications in manufacturing are superior in several aspects, especially at the scholarly level [46, 97], the direct XR applications in the disassembly scope were extracted in this section. Following the literature, the state-of-the-art XR works' strengths and drawbacks were analyzed with regard to the resolved problems, the "smart" contributions, and limited usability.

4.2.1 AR-assisted works served for disassembly planning

Before citing the previous literature, the general analysis of the ICT AR is depicted herein from the technical perspective. Among the XR applications in industrial systems, AR technology has attempted to facilitate several types of manual operations. AR has close connections with the real world. It is registered in 3D with virtual and real objects that are underlain jointly in the physical environment, and the AR system implementation consists of detection, tracking, and mixing [98]. With regard to this, the AR software development kit (SDK) cannot be neglected. Represented by Vuforia and designed for mobile devices, this platform has reduced several limitations related to attaining recognition and rendering the original 3D models [99]. Consequently, the virtual objects are animations, images, or text from a perspective determined by the camera's direction and position, and AR allows real-time blending through the developed computational design and program [98]. For disassembly and assembly operations, the real world can be enhanced, and the targeted part can be detected properly in real time.

Reference [15] designed a framework named AR-guided product disassembly (ARDIS), which played the role of the final disassembly sequence instruction for operators. The middle step and the significant part of the ARDIS was "automatic content generation," which was the transition from visual information (e.g., 3D models) and optimal sequence results to the AR guideline application [15]. The ARDIS applied AR as a pure visualization tool, and its main character was represented by the AR interface that included animated arrows and virtual instructions in the physical environment. However, this AR framework was implemented after nearly the entire disassembly planning

Table 7 Related findings for EoL aircraft parts disassembly planning

References	Relevant contributions	Selected case
[92]	The standard data source *Aircraft Maintenance Manual* for disassembly tasks	
[93]	Four EoL airframe "disassembly alternatives" and a feasibility analysis based on the disassembly difficulty	A real jet airliner carcass
[94]	Eight different disassembly/dismantling strategies under the project "Process for advanced management and technologies of aircraft end-of-life"	
[95]	A quantitative disassembly planning model to evaluate the disassembling performance based on the difficulty of discovering parameters, time spent, and material compatibility	A mid-range airliner stabilizer from a retired passenger jet

process. The assisted implications for product representation and sequence optimization were not the objectives of the AR application. The disassembly planning optimization was utilized by the score system of a disassembly sequence table (DST) [15]. Furthermore, the computational design and development processes were left out. This paper only mentioned the names of related programming techniques and languages. [14] did further research and proposed a new AR-assisted product disassembly sequence planning system (ARDIS). The new ARDIS system focused on time- and cost-optimization demands, and it built a server to store the product information and target. One of the differences from the preliminary system was that the latter was a Vuforia SDK-based application with an interactive AR user interface for component selection. Moreover, the server of this ARDIS system could provide the sequence regeneration environment [14]. In addition, the development steps from the original 3D models and server database to Unity3D were described, and the user input content of the interactive AR interface was also concerned with design. However, as a recent AR application for disassembly planning, its integration was limited since its guidelines and effectiveness were not evaluated.

Inspired by several AR-based assembly systems from the literature, [100] built an "Augmented Reality Disassembly Evaluation Tool (ARDET)" system. The output of the ARDET system could be used for a matrix-based disassembly optimization algorithm [100]. While this tool was proposed for the design stage, one of the ARDET modules, "Images Acquisition System (IAS)," was emphasized because the detection and markerless tracking functions were highlighted by it [100]. By applying the SDK "ALVAR VTT" during the IAS procedure, the 3D models could be used to track the real objects based on the stored spatial database [100]. Its AR interface assisted the objective of the genetic algorithm optimization (GAO), but there was no clear virtual–physical interaction embedded in it. The use of the leap motion sensor was integrated, and this device focused on tracking the skeletal structure of the operator's hand. [101] also developed a Vuforia SDK-based AR animation for twinning the gearbox. However, their AR application's responsibility regarding the disassembly was unclear. While this Unity3D project's process was described in detail, a considerable portion of the paper was devoted to presenting the preliminary work for the disassembly sequence selection—for instance, the graphic method based on the disassembly wave and the removal influence graph [101]. Regarding AR-assisted disassembly planning for the aviation purpose, [11] presented a system construct for targeted disassembly planning that combined the fuzzy approach and the AR application perspective. The economic output was selected as the optimization objective, and the tooling, disposal, and logistics costs were the main variables of the function. Taking into account the analysis of AR applications proposed in the mentioned literature, Table 8 summarizes these application attempts. While the integration perspective of AR technology has become clearer, examples of real-time DSP contributions remain limited. The practicability and intelligence of AR technology have not been explored deeply and exclusively for the EoL information modeling and sequence optimization phases. Furthermore, the computational design methods and development techniques of the latest AR technology have yet to be comprehended and utilized. Moreover, the advent of mature and affordable AR-related devices (e.g., compact and lightweight) has not been thoroughly investigated. According to the summary table, the exploitation of AR solutions for DSP assistance should concern the following two gaps: (1) the numerous coordinate systems should be more focused on the desired smart shop floor, and the interactions among virtual components, machines, and the devices are challenging elements, and (2) the dedicated human involvement is an inseparable element in integrating the AR-assisted system, and the responding methodical approach for EoL disassembly cannot be neglected.

4.2.2 VR-enhanced works served for disassembly planning

While AR technology could present augmented virtual objects in the physical environment, their interactivity and immersion experiences are not its competitive advantages. Assessed by a VR headset, the unique immersive user experience is obtained with multiple dimensions and nearly unlimited movement [102]. The virtual objects can be manipulated by the controllers' targeted buttons. VR represents the emergent efforts for deploying human–computer interaction (HCI), and it creates artificial 3D objects in simulated virtual environments [51, 103]. Similarly, 3D graphic tools (e.g., Rhinoceros 3D and Autodesk products) are employed to generate the virtual models, while Unity3D is the main platform for architecting the visual effects and running the programmed interaction [104]. While the use cases and implication analysis of AR and VR were clarified in the previous literature, a VR-based review of aircraft parts' disassembly–decommissioning application domains is still necessary. A survey of the best VR practices for EoL aircraft treatment is also lacking. Thus, exploring the path that VR technologies' implementation could enable is the directional task of this section.

To contemplate DSP opportunities, [105] examined the advances in ICT and highlighted the importance of the readability of the product representation modeling graph. The product geometry was illustrated as same-sized spheres (nodes) but in different colors, and these colors represented the various disassembly states. Following this, the possible disassembly paths were presented as thin cylinders that

Table 8 Recent works of AR-assisted disassembly

References	Framework	Application	Perspective	Disassembly optimization approach	Computational tools (development platforms and X-reality-enabled 3D modeling software)	Case or subject
[15]	Augmented reality-guided product disassembly: displayed the virtual arrows and 3D models (the developed given sequence and product information) for instructing the operators			Score-based disassembly sequence table	OpenCV with ArUco Markers, OpenGL with OpenGL Shading Language	Nespresso coffee machine
[100]		Augmented Reality Disassembly Evaluation Tool: produced the product representation through marker-less tracking and detection and then assisted information modeling		Disassembly strategy matrix and genetic algorithm	Unity3D, FreeCAD (for the “Exploded Assembly” function), ALVAR VTT (deployment devices: The Vuzix Glasses and LEAP Motion Controller)	Remote control
[101]		Augmented reality gearbox animation: a Vuforia-based augmented reality application		Two methods but used for the design stage: 1) graphic method based on the disassembly wave and the removal influence graph; 2) partial and/or parallel disassembly based on a disassembly precedence matrix	Unity3D, Vuforia, PTC Creo Parametric 3.0	Speed gearbox
[14]		Augmented reality-assisted product disassembly sequence planning: a Vuforia-based augmented reality application with an interactive user interface and a storage server		Multi-objective genetic algorithm based on the product interference matrix	Unity3D, Vuforia, MATLAB, MAMP	Helical gear and the third- hand assembly
[11]			The perspective of using augmented reality applications and fuzzy membership functions for the aircraft parts at the end of life	Fuzzy approach	Unity3D	Landing gear

connected the colored nodes. To better visualize the disassembly alternatives from the disassembly graph, [105] applied VR Juggler to develop and examine the disassembly visualization performance for an interlocking puzzle. Although they used an elementary open-source VR platform that was developed by a university research center, the VR vision and environment were promoted for DSP. Next, the same authors continued to explore immersive technology-assisted DSP based on the same six-piece Burr puzzle [106]. Notably, the primary focus of this paper became the uncertainties during disassembly operations, and [106] also realized that the mathematical programming of the stochastic model was not the final solution. The disassembly time and components' damage rates were integrated into the input data. Following this, the immersive technology was implemented again to derive the disassembly process and intuitive sequences. However, the utilization of immersive technology was ill-defined, and even detailed techniques and methods could not be found. Overall, the solutions of these two articles were a combination of DSP and the immersive representations' manipulation system.

In addition to the solutions for product representation and possible sequences, VR has gained widespread popularity due to the demand for it in engineering education and pre-employment safety training. With regard to related VR works in aviation, [107] developed a virtual landing gear disassembly animation system to avoid unpredictable manual risks using Unity3D and the plug-in "iTween." They formulated the automatic disassembly planning guide via programming; however, they only applied the engine Unity3D as an original animation tool. Their method neglected all of VR's intrinsic and intelligent capabilities (e.g., immersion), even though they introduced VR technology as the motivational base. In essence, their output was to model scriptable objects for the landing gear parts in a 2D environment. According to [16], the on-site operational uncertainties also included the faults caused by unskilled labor because of incorrect memory and lack of experience. Moreover, [16] applied the deep reinforcement learning (DRL) method for the adaptive disassembly planning in a VR training system. Due to the genetic algorithm (GA) being used for DSP optimization, they developed an improved DRL method known as "deep Q-network (DQN)" and made the DQN more effective with the GA. Moreover, DSP was transferred as the Markov decision process framework through the DQN. For the on-site VR training system implementation, the local server–client communication module was integrated to manage requests from Unity3D [16]. Because of this demand, the "UnityWebRequest" system was applied from the "UnityEngine.Networking" document [108]. Via the most-used VR device, HTC VIVE, a series of multi-sensory experiments was conducted to compare the disassembly time and steps. As the case was an aircraft engine, this method could be a significant advance for XR-assisted EoL aircraft disassembly research. In [16], a cloud server, the connection between Petri nets and graphic neural networks, and a stable immersive experience were the main challenges. Table 9 summarizes the presented papers. The real VR disassembly applications have considerable room for improvement; furthermore, VR is not limited to the conceptual layer. The dependence on the traditional computer-aided disassembly method should be decreased by thoroughly and properly comprehending the ICT (AR and VR) being developed.

4.2.3 The MR vision served for disassembly planning

MR is the final component of XR technology reviewed in this paper. Nevertheless, it seems to lack a universal or acknowledged definition. [54] attempted to contextualize MR technology through experts' interviews and literature surveys; based on their theoretical derivation, six independent notions were found by analyzing different characters (e.g., environment, input–output, and immersion). The most popular understanding that numerous researchers have agreed upon is the notion of a "reality–virtuality continuum" [52, 54]. MR has been placed on this continuum from completely physical environments to computer-generated immersive ones [52, 53]. In the present study, MR is described as an agile vision that is not yet an established application perspective. For example, [109] designed an interactive user interface for applying the MR vision to aircraft components' visual inspection. In the system they developed, the inspector and expert could see a physical aircraft component or its virtual twin remotely, and the damage degree of the component structure could be analyzed. Unity3D, the "MixedRealityToolkit" system and AR glasses ("Microsoft HoloLens") were used [109]. This method served as an integrated user interface, but it could engender further ideas for solving the complex aircraft decommissioning documentation, the targeted interlocking assemblies, and the non-destructive disassembly. The prior research on DSP works that was facilitated by the advent of AR/VR/MR technologies is documented in this section. This review also helps characterize the existing XR-based applications and systems for DSP. According to the presented applications in the rigorous "reality" classification, the various XR-assisted DSP could be utilized independently or cooperatively.

4.3 The second phase of the integrative infusion antecedents: XR–lean-assisted DSP

The central aim of this study is to remark on the joint integration of XR and lean. Based on the theoretical background of the relevant works, I4.0 could not displace the philosophical lean. However, the evidence for the joint application of lean and I4.0 technologies remains insufficient. The majority

Table 9 Related technical work of VR-assisted disassembly operations

Literature	Outputs (applications, systems, frameworks, and platforms)	Disassembly optimization approach	Computational design tools (development platforms and X-reality-enabled 3D modeling software)	Case or subject
[105]	An interactive VR Juggler-based project examining the disassembly graph	Node-based hierarchical graph	VR Juggler (device: Nintendo Wii Remote)	Six-piece Burr puzzle
[106]	The combination of the stochastic programming model and intuitive sequences' visualization in an immersive environment	A stochastic programming model with a "cost structure" to minimize the total disassembly time	General immersive computing technologies	Six-piece Burr puzzle
[107]	A virtual 3D landing gear disassembly modeling and animation system		Unity3D, iTween, 3ds Max	Landing gear
[16]	A deep reinforcement learning-based disassembly sequence planning in a virtual reality training system	The deep reinforcement learning method optimized by the genetic algorithm, disassembly Petri net modeling	Unity3D, UnityWebRequest system, 3ds Max (device: HTC VIVE)	Aircraft engine

of the previous studies presented the proof-of-concept correlations between lean principles and I4.0 systems in an abstract context. In this section, the collaboration of lean and XR is surveyed from a more practical perspective.

According to the existing research, lean principles and I4.0 technologies—or lean tools and I4.0 principles—could be reinforced by each other [110, 111]. In essence, a significant portion of the work published up to now has focused on one-sided conceptual capability. In line with the "Lean Manual Assembly 4.0" proposed by [82], lean could be a rational starting point for implementing I4.0-generated changes to produce performance benefits. [110] defined the term "Lean 4.0" and, in terms of the correlation, determined that I4.0 could exert a compensatory effect on lean's shortcomings. [110] also stated that lean processes were the basis of feasible I4.0 technology implementation. In particular, VSM 4.0, VM 4.0, and Poka-yoke 4.0 were mentioned because these rely on real-time data mechanisms and XR devices: the XR display could support stakeholders in receiving real-time value streams remotely through VSM 4.0, while the role of XR in VM 4.0 and Poka-yoke 4.0 was to handle standardization and correction improvements. More specifically, [110] employed AR as a virtual visualization tool for replacing the physical boards in VM 4.0 and also used AR to support zero-error picking operations in Poka-yoke 4.0. Table 10 summarizes these potential correlations by [110]. From a diverse perspective, [17] categorized the implications of I4.0 technology competence for lean principles based on four-level capability degrees. The four levels of I4.0 technologies' competences that they used had been proposed by [112]: monitoring, control, optimization, and autonomy. AR was the unique XR technology their study engaged with, and the potential implications for the lean principles of AR are shown in Table 11. Notably, for AR, the "monitoring" level was the only matched I4.0-based capability when influencing various lean principles. The illustrated lean principles were jidoka, people and teamwork, and foundations. Although the examination visions of [17] and [110] differed, their findings were similar due to the inherent connections. As Table 11 shows, the lean tools included error-proofing, stable and standardized processes, and VM. Therefore, the XR–lean use could be integrated into value profile tracing and tracking services for multi-stakeholders remotely. As [113] presented, the visual techniques were ubiquitous and valuable factors, and they reflected the evident features of lean. Similarly, [114] described a digital VS system and proposed ideal visual tools, which also included XR technologies. Moreover, the corrections in the standardized process and the guidance in the training process were major contributions to the desired performance benefits. However, these elementary conclusions could also be limited by the knowledge gap from the manifold competences of XR. AR has gained widespread attention in discussions of I4.0 and lean, but VR and MR are also powerful techniques that can

Table 10 The potential correlation between "Lean 4.0" and XR (the source of information: [111])

XR	Lean 4.0	Potential correlation
The role of a visualization tool	VSM 4.0	The remote controlling of real-time value streams
	VM 4.0 and Poka-yoke 4.0	Standardization and correction improvements Augmented reality: (1) replace the physical boards in VM 4.0 and (2) support zero-error picking operations in Poka-yoke 4.0

Table 11 Capability level (monitoring) of AR impacting lean principles (the source of information: [17])

Monitoring	Lean principles	Lean tools
Augmented reality	Jidoka	Error-proofing
	People and teamwork	Cross-trained
	Foundations	Continuous improvement
		Stable and standardized processes
		Visual management

assist reconfigurable monitoring systems. Furthermore, the control, optimization, and autonomy impact levels could be explored when applying XR technologies.

All the major XR–lean research showcases were focused on the training performance improvement of individual operators, especially in architecture, engineering, and construction. [115] compared the operational time before and after AR engineering education by assessing machining and dimensioning activities on machine tools. The experimental object was originally designed as a lean process, and the cost and time data with and without the AR application were collected and differentiated. The savings were calculated at the end, and the positive effects were proven. While the examined activity was not disassembly, the measurement and comparison of the time and costs of lean training could be a valuable method. Thus, lean training and lean education have been devised as typical XR use cases. However, according to the workshops conducted and questionnaires issued by [49], the industrial XR use cases could involve stakeholder engagement, design support, and management support in addition to training. For example, [116] attempted to provide an operable explanation for integrating directional lean principles into EoL aircraft disassembly sequencing. Considering the size and complexity of the aircraft, the objective of minimizing operating zones and movements was derived from the analysis of independent lean principles for EoL aircraft disassembly [116]. An optimal disassembly path among the various working zones was the desired output, and a disassembly graph had to be generated first to display all possible zones and paths. After the operating zones were defined, the availability of each zone was evaluated and compared using the ratio between the number of available tasks and total tasks. This lean disassembly sequencing method could be further developed as a conventional foundation when applying XR.

5 A research agenda: smart disassembly sequence planning (SDSP) for complex EoL products

It is particularly crucial to explore the transformative impact and collaborative potential of XR–lean joint integration in this emerging research. [117] and [118] stated that implementing a systematic review also entails the identification of promising future research agendas and directions. The present paper has already realized and engaged with the conceptual boundaries in dynamic applications and services for disassembly activities; however, a broader agenda for further research should also be derived. Moreover, a fundamental construct must be proposed for guiding the future usage of the recovered complex products at the technical and strategic levels. After comprehending the results of the previous studies through the review analysis, a generally and relatively accepted definition of a future revenue-generating measure is discussed in this section.

Enhancing the awareness and understanding of the topic area should be addressed. Essentially, a digitally empowered environment necessitates a deep understanding of various disciplines. In terms of the systematic review presented in this study, the proposed research agenda is defined to further discuss a broader application engagement, namely complex EoL products. As previously noted, used aircraft and most high-value parts are representative complex EoL products. To manage disassembly operations more economically, a digitalized DSP should be proposed under the constant development of sustainability and digitalization. As the correlations among I4.0, XR, lean, and disassembly from academic-practitioner literature have already been analyzed, there is clear evidence that proper

XR–lean usage would be superior to traditional DSP. For instance, the automation and visualization of disassembling procedures are significant contributions. Based on the detailed content analysis of extant publications in the previous section, this study proposes a future agenda, SDSP, regarding complex EoL products. To attain a full-scale SDSP agenda, the decision-making methods facilitated by a compatible development platform, interactive devices, and intelligent resources (e.g., models and algorithms) could be the solution approaches [119]. Therefore, SDSP is merged to be a concise frame and general attitude that involves technological and managerial enablers (XR and lean). In the following, the discussion on the proposed agenda concerns two parts: (1) the conceptualization of SDSP, and (2) research gaps, open challenges, and future opportunities of SDSP.

5.1 Conceptualizing "SDSP"

To streamline the presentation of a research agenda specific to the EoL disassembly requirements, this section identifies gaps through the definition of SDSP and its built-in technology and management development plans. SDSP is the result of following the flow presented in Fig. 1. The conceptual planning path of SDSP is naturally organized to boost the role of XR–lean combination in a wider environment and coordinates reverse supply chains. Consistent with the intention of this study, which has reviewed the literature on XR–lean DSP, the conceptualization of SDSP begins with the implications of I4.0 and serves lean disassembly with XR technologies. SDSP refers to a productivity-enhancing disassembly decision-support construct that optimizes operative manners with the strong assistance of XR and lean. SDSP provides, shares, and virtualizes the information upon which planners make effective decisions in real-time mode [120]. To make precise use of the intra-resources on information and computer technology (i.e., XR) and management principles (i.e., lean), SDSP aims to generate an advisable plan that best satisfies different business goals and constraints under uncertainty. Achieving sustainable operational excellence by SDSP is one of key determinants of improving the value of reverse logistics and recovery activities in the circular value chain holistically. SDSP is expected to create a favorable impact by broadening the view of digital disassembly transformation.

The fundamental idea behind SDSP is to be "smart," which serves as the foundation for future research. Similarly, as a growing research area, SDSP responds to the broader call for "smart" research. "Smart" offers an indispensable foundation and elevates the importance of technology for improving product recovery business. Regarding the context of I4.0-based disassembly, the relevant term "smart disassembly" only occurred once in [121]. They presented "smart disassembly" as one of their eight disassembly/dismantling strategies (e.g., "smart shredding" and "systematic disassembly") and focused on the recycling development case of EoL aircraft [121]. However, they described "smart disassembly" as a type of time-saving strategy rather than a detailed operational solution with enabling technologies. Their "smart disassembly" had no direct connection to I4.0 or other revolutionary paradigms, and the aim was identified as avoiding removing the components with similar material composition. "Smart disassembly" was recommended, but the "smart" implication was limited compared to other proactive concepts, such as "smart factory" [122], "smart manufacturing" [123], and "smart remanufacturing" [43], that were driven by I4.0. "Smart" can be a core competency involved in the development of technological advances. To launch I4.0 initiatives, SDSP should leverage the full potential of laying I4.0 technologies and systems. This proactive approach of emphasizing "smart" is necessary to ensure that disassembly planning can continuously adapt to digitalization. Since "smart" spans a wide range of digital technologies theoretically, more attention can be paid to XR technology, as integrating non-essential technologies could result in wasting capital expenditure. This can also help reflect the actual needs and advance industrial service-oriented applications that require detailed digital fulfillment. In the present study, the underlying logic of SDSP is still strongly relevant to the interactive relationships of I4.0–lean. With the advent of lean, the functions of complementarity and continuous learning can be tightly integrated into SDSP. Under the promise of operational excellence, for instance, the creation of customized services can align with multi-target and partial disassembly planning. This can underpin SDSP to cope effectively with changing customer demands.

5.2 Research gaps, open challenges, and future opportunities of SDSP

Building upon this foundational review, earlier research has explored several possibilities for combining XR and lean in DSP. Apart from drivers, advantages, and barriers, potential conflicts should also be uncovered. In this section, we identify gaps and challenges in technology and management development and offer clear insights into future directions. In the following, our discussions are categorized in three aspects: (1) system development in the circular value chain, (2) technology requirements and adoption improvements, and (3) associating SDSP with other multidisciplinary domains and perspectives. Agenda-based descriptions corresponding to the gaps and opportunities are summarized in Table 12.

Table 12 Smart disassembly sequence planning

Categories	Research gap	Agenda-based description for hot spots
1	System development in the circular value chain	1A. Understand how value chain-related circular economy knowledge influences the execution of the smart disassembly sequence planning system 1B. Carry out more normative research to take the system perspective into account and exemplify how to gradually cooperate with higher levels of enterprise systems development 1C. Apply the vertical integration method to explore the functional layers of the interconnection networks of the smart disassembly sequence planning system
2	Technology requirements and adoption improvements	X-reality content: 2A. Develop more technical and managerial support for preserving X-reality content 2B. Put more research efforts on bi-directional linkages and information exchange standards between CAD models and X-reality models 2C. The accuracy of illusory images in stereoscopic animations can be applied to assess the applicability and usefulness of X-reality content 2D. Address how the design and development of industrial X-reality user interfaces influence competitive aspects of smart disassembly sequence planning 2E. Connect autonomous disassembly decision-making processes with the automation of X-reality systems 2F. Carry out more research through expert interviews for the full deployment of X-reality technologies and enhance the sample of professionals and academics X-reality experiences: 2G. Explore innovative ways of recording and tracing the users' experiential experiments precisely when interacting with X-reality applications 2F. More focus should be given to experiment-based empirical research and practical validation on X-reality disassembly
3	Associating smart disassembly sequence planning with other domains and perspectives	3A. Broadening the perspective to cooperate with other smart technologies and unpacking the effect of employing manifold digital and smart systems for a prevailing digital disassembly transformation 3B. Expand the research focus to encompass the emerging wave of Industry 5.0 and prioritize the human-centric perspective in a systematic manner

5.2.1 System development in the circular value chain

While traditional DSP are deeply rooted in the operations area, SDSP could implement a wider focus to enable digital processes smoothly and improve decision-making efficiency. The combinative effects of given XR and lean also influence opportunities of extending SDSP, as both serve multiple constituencies. To grow as a robust techno-centric unit, understanding and constructing the system of SDSP are critical. The complementarities and conflicts of the SDSP system development cannot be ruled out. SDSP is proposed as a promising research pattern in the present work. Developing a limited version of smart remanufacturing might be needless. Motivated by digitalization, SDSP is not limited to a product-dependent system. Broadly speaking, SDSP is intended to be embedded in the enterprise systems of the sustainable manufacturing sector. The SDSP system, with the emphasis on planning, should be capable of dealing with management and control to make the information more readily available for determining the optimal sequence. SDSP, in future research, could provide inputs to distribution, financial, and marketing systems that request the information [120]. However, some questions have arisen due to shortfalls at the system level that can incorporate disassembly, which is an important part of remanufacturers' value chain.

Based on our bibliometric visualization findings in Section 3.2.3, we learn that circular economy is crucial in remanufacturing because it promotes circularity of network flows [124]. A higher employment of theoretical knowledge based on circular economy might affect disassembly. Although previous research covers a range of circular economy initiatives and implications on EoL treatment research, the differences in "smart" shifts need further investigation. The reverse logistics and recovery processes are partly referred to as circular value chain processes [125]. Regardless of operations or technology development, they represent primary activities of the entire value chain merely. Also, the managerial areas of disassembly are usually not discussed as a directional topic in the previous studies but are rather treated as a side topic. Deriving the system architecture in an isolated manner might hold research back. While much technological progress has been made in the wave of I4.0, as like we considered the necessity of integrating lean, it is also imperative to explore more potential methods for efficient organizational improvements. Therefore, it would be valuable to understand how value chain-related circular economy knowledge influences the execution of the SDSP system. To examine more challenges and chances of SDSP at the firm level, it is advantageous to consider the fields of knowledge in circular economy and value systems [125]. It might also be of specific interest to investigate how to match the SDSP system with the needs of different remanufacturing companies' value chains. The variety of remanufacturing companies could include independent remanufacturer and original equipment remanufacturer. Overall, more normative research is needed to exemplify how to cooperate higher levels of enterprise systems development gradually [49]. Vertical integration can be an interesting method to reinforce the adaptability of the SDSP system in a more organized manner. Vertical integration refers to considering relevant systems development at all hierarchical levels of the remanufacturing company. This can also provide an opportunity to explore and classify the lesser-known layers differing in functional domains for future propositions of the SDSP system.

5.2.2 Technology requirements and adoption improvements

In the SDSP proposed by this study, XR is a typical allocation of smart elements. Industrial XR applications are increasingly mature, but the capacity to handle some technological issues is still limited. Moreover, as our review reveals, XR is still under-investigated in remanufacturing applications. This section compiles the technological requirements and potential adoption improvements of XR-assisted disassembly. XR content and experiences are selected to introduce considering the technological perspectives.

XR content Our review analysis highlights that XR content could contribute to operative and decision-making support. As a practice-led initiative, the role of XR is to generate positive effects on smart decision-making in SDSP. To serve complex EoL products, XR-ready models can be complex and large during the disassembly information modeling process [49]. Meanwhile, efficient operations need the support of real-time simulation from XR. Therefore, large memory and processing capacity are required for the development and preservation of XR content. Besides, only several software tools can convert between CAD models and XR-ready models directly, but research efforts on bi-directional linkages and information exchange standards are still limited. Solutions to restrain these negative impacts can help use XR to deal with modeling and predicting rigorously. The accuracy of illusory images in stereoscopic animations can be an aspect to assess the applicability and usefulness of XR content. The components should be detailed to display in XR applications. Since XR is a relatively ideal technology to visualize uncertainty, an accurate virtual product representation should be attained for the operational trust [49]. Based on this, the outcomes of SDSP can be trustworthy. In most circumstances, the effects of XR instructions and guidelines rely on the design and development of user interfaces. For instance, optimal action plans can be displayed in XR applications that authored by SDSP. The role of interfaces exists in the task of managing XR content. Another issue is the usage of the automation in XR systems. Most of the common achievements (e.g., the visualization display of virtual assets and scriptable actions in virtual scenarios) could be attained directly via programming. This advancement could assist autonomous decision-making processes and reduce steps in SDSP. Summing up, more knowledge is needed for the deployment of XR technologies. Research that elaborates on multiple valuable insights from interdisciplinary expert interviews can provide more findings in the future. Therefore, there is still space for applying qualitative and mixed methods.

XR experiences The technology-mediated experiences generated by XR are crucial for any sector. Training and onboarding for existing workforces and novices on the use of innovative XR systems are vital for physical operational implementation. For disassembly planning, recording and storing the users' experiential experiments precisely when interacting with XR applications are desired functions. In other words, there is a need to observe and access other user experiences in the same situation (e.g., the wholly same VR environments), yet experiment-based empirical studies are still in the early stages of XR-assisted disassembly development. The data obtained from user experiments can be a reliable source of decision analytics for the collaboration of remote and on-site workers, or a sufficient source of knowledge-perceiving assessment for unskilled operators. However, the drawback of the current tracking devices may hinder the progress of archiving and assessing detailed XR experiences. A "social VR" [126] perspective could be an applicable starting point due to the multi-stakeholder engagement journey in the general remanufacturing organization.

5.2.3 Associating SDSP with other multidisciplinary domains and perspectives

There is potential for further theoretical research on the positive outcomes of SDSP. Although disassembly is an industrial process, SDSP is a cohesive foundation aiming to generate positive effects by developing flexibly managed disassembly operations. However, existing research on future perspectives across academic disciplines is not comprehensive. To avoid obstructing interconnection and communication among research communities, we emphasize potential studies on associating the development paths of SDSP with other domains. Two areas are worthy of noting here: (1) cooperating with more smart technologies, and (2) concerning the role of humankind.

Cooperating with more smart technologies At present, the "smart" enhancement of the proposed SDSP relies on a particular approach, specifically the close collaboration with XR to outline the technical characteristics of the current SDSP. Other I4.0 technologies are temporarily disregarded due to the original intention of concrete contribution from applying XR individually. However, unpacking the effect of employing manifold digital and smart systems for a prevailing digital disassembly transformation could be the fuel to spark future investigation. It is of great advantage to connect deeper insight regarding other I4.0 technologies in theory and practice, and the collaborations among various I4.0 technologies have gained enough attentions [89]. However, utilizing overarching I4.0 capabilities with respective features are still relatively lacking, as well as integrating with XR systems in detail. From our bibliometric visualization in Fig. 10, it can be observed that DT plays a vital role as integrating XR applications. XR and DT could develop themselves as a collaborative topic area [12]. Considering the previously discussed challenges in Section 5.2.2.1, the engagement of IoT devices [2] could provide real-time data for improving correctness and effectiveness of XR images. Importantly, the accurate integration of IoT sensors can connect data that processes in different phases of the product life cycle. From the whole review on XR-assisted DSP and XR–lean applications, the main responsibility of XR toolchains is not focus on ensuring the information security and privacy [49]. Addressing security and privacy issues during the disassembly planning could drive a bold focus shift for XR. For the successful implementation of elaborating SDSP in an environment that evolves around digital technologies, the digitalization measurement of SDSP cannot be avoided in next confirmatory research.

Concerning the human-centric perspective and Industry 5.0 To inspire further research and exploration, the role of humans in SDSP could connect insights from the wave of Industry 5.0 phenomenon. Coexisting with I4.0, Industry 5.0 connects a sustainable and human-centered paradigm and I4.0 technologies, even though it might be a premature concept [127]. It can be an opportunity to uncover the uncertain impacts from this new industrial paradigm and pinpoint the other hidden needs. A predominant focus on the human-centric perspective can be considered to enhance the already existing research approaches. Section 5.2.2.2 calls for more intuitive and implicit interactions within the scope of XR technology. Meanwhile, reducing the problems of human well-being and security can be a long endeavor along with new benefits and barriers. These considerations could be a framework synthesis through closer proximity to XR because XR offers multi-modal HCI. These additional studies will help to find more practical implication for the future SDSP.

6 Conclusion

This study contributes to the intelligent disassembly and computer-aided remanufacturing in the literature through a comprehensive literature review and an actionable research agenda. DSP is an essential part of EoL management flow. Since its cost-effectiveness and environmental benefits are recognized, advancing disassembly management can be presented as a business opportunity, and the practice research needs abundant evidence for the rationalization of digital technology adoption. This paper employs a structured literature review to combine two enablers, XR and lean, in the I4.0-driven DSP for aircraft parts at the EoL stage. As conceptual discussions alone are insufficient to facilitate XR–lean integration, this review investigates the current state of the practice of DSP to unlock more transformative opportunities for XR applications and lean implementation. By reviewing the operable methods from the existing literature, the benefits that XR and lean can bring to DSP are revealed. SDSP is defined as a novel possibility or environment for closer collaboration and interactivity among humans, computers, equipment, and machines. SDSP is a transitional frame that can shape the conceptual understanding of DSP using I4.0. Notably, the collaboration between computational intelligence and scientific management is nearly absent, and the same can be said for radical improvement in flexibility and efficiency. To comprehensively address the challenges of applying XR technologies for lean improvement purposes, this review presents two steps for analyzing XR and lean on the basis of SDSP. The relevant application-based work of XR is examined through the assistive devices and assistance systems in disassembly; following this, the collaboration between XR and lean is explored while considering the XR capability, lean principles, and lean tools. From the existing research findings, it can be concluded that XR–lean integration has the potential to improve the digitalization, quality, and effectiveness of EoL DSP. Moreover, designing and coordinating an XR–lean-aided decision support tool is the outcome of the joint consideration of I4.0 and lean impacts. However, to reinforce the future applicability and usefulness, XR integration should be assessed across the theorization measurement, application development, and performance analysis with regard to lean-based disassembly. As XR devices are wearable, the ergonomics analysis of human–XR collaboration cannot be lacking. For the future realization of the final objective of digitalized DSP and predictive analytics, the vital issues include the XR–lean approach to solving the uncertain EoL condition and enhancing value creation. Furthermore, the testing and validation from case studies and experimental studies should be implemented in the decision-support system to verify the XR–lean method to meet the managerial practices requirements of EoL aircraft parts. In addition, the future selected cases must be proper aircraft parts' DSP scenarios for the lean management and XR visual analytics. Overall, future research can include the measurement and analysis of the efficiency and social sustainability impacts of EoL aircraft parts' cases.

Abbreviations *AEC*: Architecture engineering and construction; *AMM*: Aircraft Maintenance Manual; *AR*: Augmented reality; *ARDET*: Augmented Reality Disassembly Evaluation Tool; *ARDIS*: AR-guided product disassembly; *APUs*: Auxiliary power units; *BIPAD*: Best industry practices for aircraft decommissioning; *BOM*: Bill of materials; *CPS*: Cyber-physical systems; *DQN*: Deep Q-network; *DRL*: Deep reinforcement learning; *DST*: Disassembly sequence table; *DT*: Digital twin; *ECS*: Environmental control systems; *EoL*: End-of-life; *FATP/T*: Fuzzy attributed and timed predicate/transition net; *FOV*: Field-of-view; *FRPN*: Fuzzy reasoning Petri net; *GAO*: Genetic algorithm optimization; *GrICT*: Green information and communication technologies; *HCI*: Human–computer interaction; *HHD*: Hand-held display; *HMD*: Head-mounted device; *I4.0*: Industry 4.0; *IAS*: Images acquisition system; *IATA*: International Air Transport Association; *ICAO*: International Civil Aviation Organization; *ICT*: Information and communication technology; *JIT*: Just-in-time; *LLPs*: Life-limited parts; *IoT*: Internet of things; *MR*: Mixed reality; *NP*: Non-deterministic polynomial; *OEM*: Original equipment manufacturer; *PAMELA*: Process for advanced management of end-of-life aircraft; *RQs*: Research questions; *SD*: Science direct; *SDK*: Software development kit; *SDSP*: Smart disassembly sequence planning; *TCCs*: Time-controlled components; *VM*: Visual management; *VR*: Virtual reality; *VSM*: Value stream mapping; *WoS*: Web of Science; *XR*: X-reality

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Declarations

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