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**Integrating X-reality and Lean into End-of-Life Product Disassembly Planning
in Industry 4.0 and Industry 5.0: A Critical Review**

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
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Ce mémoire intitulé :

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présenté par **Yinong YANG**

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DEDICATION

*To my beloved parents, my fiancé, and myself.
To all the amazing people sharing experiences and thoughts with me.*

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RÉSUMÉ

La récupération de la valeur des produits en fin de vie (EoL) et la fermeture de la boucle des composants industriels sont des alternatives durables et efficaces, nécessitant des efforts dans les activités de remanufacturing. La désassemblage, une étape clé dans la remanufacturing et l'opération la plus difficile dans les processus EoL, nécessite souvent une main-d'œuvre intensive et des processus novateurs. Les opportunités de recherche abondent pour faire progresser la planification de désassemblage des produits EoL, attirant les chercheurs et les praticiens. Cette thèse de maîtrise étudie deux évolutions industrielles existantes, l'Industrie 4.0 et l'Industrie 5.0, car le désassemblage traditionnel implique des changements de paradigme.

L'Industrie 4.0, un paradigme axé sur la technologie, vise à améliorer l'efficacité, la productivité et la personnalisation. La deuxième vision centrale appliquée dans cette étude est l'Industrie 5.0, représentant un cycle d'adoption plus durable, plaçant les initiatives centrées sur l'humain et la société au centre des systèmes de fabrication/production. Cependant, la recherche explorant leurs rôles dans le domaine du désassemblage EoL fait défaut.

Le point de départ de la transformation numérique du désassemblage découle de complexités (par exemple, les réglementations environnementales et ergonomiques) et d'incertitudes (par exemple, la demande commerciale, les quantités de produits, les informations structurelles et les coûts d'exploitation). Pour relever ces défis, la planification du désassemblage nécessite des systèmes de prise de décision novateurs avec des outils numériques adaptés pour plusieurs contraintes. Dans ce contexte, X-réalité (XR) et lean sont adoptés conjointement en tant qu'acteurs techno-fonctionnels et managériaux dans le cadre de l'Industrie 4.0 et de l'Industrie 5.0. XR fusionne les mondes virtuel et physique, réduisant les incertitudes en tant qu'outil de simulation ou d'assistance de visualisation cognitive. Lean assure la continuité des activités en éliminant les gaspillages de processus et en offrant une amélioration continue, en considérant l'humain comme un facteur fondamental.

Cependant, il existe un manque de preuves théoriques suggérant que la planification du désassemblage des produits en fin de vie peut être facilitée par l'adoption de la XR et du lean dans le contexte de l'industrie 4.0 et de l'industrie 5.0. De plus, il existe peu de lignes d'action ou de cadres dans la littérature concernant les possibilités de combinaison de l'industrie 4.0, de l'industrie 5.0, de la XR et du lean pour le développement durable dans la planification du désassemblage. La littérature passée manque d'aperçu des synergies entre la XR et le lean dans la recherche sur le désassemblage sous l'impact de l'industrie 4.0 et de l'industrie 5.0.

L'objectif de cette thèse est d'explorer ce que l'Industrie 4.0 et l'Industrie 5.0 signifient pour

la planification du désassemblage dans la gestion des produits EoL. Afin de répondre à cette question de recherche, cette étude a l'intention de fournir un compte-rendu de la planification du désassemblage des produits EoL avec l'intégration conjointe de XR et de lean, basée sur les résultats de la littérature existante. La thèse plaide en faveur d'actions visant à faciliter la circulation libre de l'information, en utilisant des revues systématiques de la littérature pour comprendre les combinaisons possibles de XR et de lean dans le domaine du désassemblage. En outre, la thèse présente les travaux préliminaires pour discerner les recherches en cours en développant un cadre basé sur l'Industrie 4.0, "Smart Disassembly Sequence Planning (SDSP)", ainsi qu'un cadre intégré centré sur Human-Centric, Smart, and Lean (HSL) dans le contexte de l'Industrie 5.0. Enfin, la thèse développe le cadre en identifiant les orientations futures de recherche. Nos résultats mettent en évidence les lacunes émergentes et les tendances de recherche viables, tout en offrant des constructions collaboratives et co-créatives pour faire avancer la transformation numérique du désassemblage. Contrairement aux autres critiques, cette étude constitue une référence éclairante pour les orientations futures dans les opérations de désassemblage et les solutions de réalisation numérique.

ABSTRACT

Recovering the value of end-of-life (EoL) products and closing the loop of industrial components are sustainable and efficient alternatives, requiring efforts in remanufacturing activities. Disassembly, a dominant step in remanufacturing and the most challenging operation in EoL processes, often requires human-intensive labor and novel processes. Research opportunities abound in advancing EoL product disassembly planning, attracting scholars and practitioners alike. This master's thesis studies two existent industrial evolutions, Industry 4.0 and Industry 5.0, as traditional disassembly entails paradigmatic shifts.

Industry 4.0, a technology-driven paradigm, aims to improve efficiency, productivity, and customization. The second centric paradigmatic vision applied in this study is Industry 5.0, representing a more sustainable adoption cycle, placing human-centric and society-centric initiatives at the center of manufacturing/production systems. However, research exploring their roles in the EoL disassembly domain is lacking.

The starting point of digital disassembly transformation stems from complexities (e.g., environmental and ergonomic regulations) and uncertainties (e.g., marketing demand, product quantities, structural information, and operating costs). To address these challenges, disassembly planning needs novel decision-support systems with appropriate digital tools for multiple constraints. In this context, X-reality (XR) and lean are jointly adopted as techno-functional and managerial enablers under Industry 4.0 and Industry 5.0. XR merges virtual and physical worlds, reducing uncertainties as a simulation tool or cognitive visualization assistance. Lean ensures business continuity by eliminating process waste and offering continuous improvement, considering humans as a fundamental factor.

However, there is a lack of theoretical evidence suggesting that EoL product disassembly planning can be facilitated by the adoption of XR and lean in the context of both Industry 4.0 and Industry 5.0. Moreover, few agendas or frameworks exist in the literature concerning the combinatorial possibilities of associating Industry 4.0, Industry 5.0, XR, and lean for sustainable development in disassembly planning. The past literature lacks insight into the synergies of XR and lean in disassembly research.

The purpose of this thesis is to explore what Industry 4.0 and Industry 5.0 mean for disassembly planning in managing EoL products and how the collaboration of XR and lean can play techno-functional roles to facilitate the design of decision-support systems. To overcome this research gap, this study intends to offer an accurate but succinct account of EoL disassembly planning with the joint integration of XR and lean based on the findings from the extant

literature. The thesis advocates for actions that facilitate barrier-free information flow, using systematic literature reviews to comprehend the possible combinations of XR and lean in the disassembly domain. Additionally, the thesis presents the preliminary work aimed at discerning ongoing research by developing an Industry 4.0-driven agenda, "Smart Disassembly Sequence Planning (SDSP)," and an integrated Human-Centric, Smart, and Lean (HSL) framework within the context of Industry 5.0. Finally, the thesis elaborates on the agenda and framework by identifying future research directions. Our findings not only underline emerging gaps and viable research trends but also offer collaborative and co-creative constructs to advance digital disassembly transformation. In contrast to other critical reviews, this study serves as an insightful reference for future directions in disassembly operations and digital fulfillment solutions.

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LIST OF SYMBOLS AND ACRONYMS

3D	Three Dimensional
AEC	Architecture Engineering and Construction
AI	Artificial Intelligence
AMM	Aircraft Maintenance Manual
AR	Augmented Reality
ARDET	Augmented Reality Disassembly Evaluation Tool
ARDIS	Augmented Reality-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
GAO	Genetic Algorithm Optimization
GrICT	Green Information and Communication Technologies
HCI	Human–Computer Interaction
HHD	Hand-Held Display
HMD	Head-Mounted Device
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

CHAPITRE 1 INTRODUCTION

This chapter is divided into four sections : (1) the description of the research context, (2) research questions, (3) research objectives, and (4) the general organization of the thesis.

1.1 Context

The calls for developing decision-support systems for managing end-of-life (EoL) products have rapidly grown. When a product approaches the end of its economic or operational life, remanufacturing and restoring it to like-new conditions represent a business opportunity as sustainability has become the primary consideration in the current diversifying and growing society. To collect EoL products that will eventually be recovered as second-hand items, returned products need to be disassembled first [4]. From an operational perspective, disassembly refers to the manner of separating EoL products before a series of restoration activities [5]. Disassembly is an unavoidable step and the most challenging operation in EoL processes. Disassembly can be a decisive factor in increasing productivity and profitability in remanufacturing and reverse supply chains. Positive impacts of disassembly planning include the combinatorial optimization of disassembly steps, task assignments, and line balancing [6]. Therefore, generating optimal EoL product disassembly plans towards reuse and remarketing becomes a viable tactic for improving recyclability and economic growth. In the context of environmental, social, and economic sustainability, it is imperative to explore potential improvements in disassembly planning.

Within the period of global industrial transformation, Industry 4.0 or the fourth industrial revolution has increased its economic attractiveness. Industry 4.0 leads the actions on increasing the efficiency and flexibility of manufacturing/production systems [7]. Industry 4.0 is characterized by technological advancements, and industrial scenarios can benefit from the integration of its digital empowerment [8]. The burgeoning uptake of emerging technologies (e.g., big data analytics, augmented reality (AR), virtual reality (VR), digital twin (DT), artificial intelligence (AI), and internet of things (IoT)) supports the practical pillars of Industry 4.0 to foster relatively smart practices [9]. Industry 4.0 connects these technologies and operational systems in a cyber-physical system (CPS) manner within an Internet-fueled environment. With aims of improving operations capabilities and long-term profitability, digitally enabled manufacturing modes can be architected to gain a competitive advantage under the impact of Industry 4.0. This trend also pushes EoL product management to explore the detailed adoption of technology to facilitate decision-making processes with Industry 4.0

initiatives.

While a growing body of research related to disassembly planning has been investigated in the setting of digitalization, managing the returned EoL products with cost efficiency-oriented thinking is not enough. Industry 5.0, or the fifth industrial revolution, emerges in the face of a constant quest for sustainability and competitiveness. As an evolutionary vision, Industry 5.0 centers on humans and societal needs. Even though Industry 5.0 can bring additional value across the resilience, sustainability, and human-centric perspectives, digital technologies offered by Industry 4.0 are incorporated into Industry 5.0 [10]. Therefore, both Industry 4.0 and Industry 5.0 are profoundly impacted by emerging technologies.

Among all enabling technologies, X-reality (XR) falls under the broad terms of “Industry 4.0” or “Industry 5.0” [11]. It can be deemed as an important technological component of both Industry 4.0 and Industry 5.0 [12]. In this thesis, "X" is differentiated as an attribute or preference variable. X-reality (XR) is a comprehensive set of information technology that encompasses various virtual-physical technologies, including AR, VR, mixed reality (MR), and so forth [13]. XR creates illusory images or stereoscopic animations through digital image processing and computer graphics. It can extend the memorability when interacting with graphics-aware objects are compared. By merging virtual-physical environments, XR can reduce the need for physical information transmission. The real-time interaction that XR provides is achieved through wearable devices or mobile applications [14]. To date, considerable studies have concluded that the conventional solution of disassembly planning embraces structural information modeling and the application of optimization algorithms [5]. Therefore, the pathways of incorporating XR into disassembly preparations and operations can be divided into two parts : (1) providing special visual effects, the synchronization of physical and virtual scenarios, and human-computer interaction for operator training, engineering education, and remote collaboration between experts and operators ; (2) applying virtual replicas to simulate the shop floor or structure information of production to conduct spatial reasoning and comparison during decision-making processes [15].

A managerial approach is also required to assist and monitor the entire disassembly process for constant operational improvements (e.g., reducing processing time and human displacements). To avoid engendering unbalanced outcomes due to numerous digitalized initiatives in remanufacturing businesses and organizations, lean is integrated as a management system into both Industry 4.0 and Industry 5.0 paradigms. Moreover, the built-in characteristics of lean advocate decreasing the consumption of resources, resulting in the reduction of environmental pollution. Through the application of appropriate lean tools, environmentally conscious companies can also meet the requirements of occupational well-being [16].

1.2 Research questions

- What is the current state regarding the disassembly planning of EoL products from the perspectives of Industry 4.0 and Industry 5.0? How can Industry 4.0 and Industry 5.0 promote EoL disassembly planning?
- What are the current trends in the association of XR and lean in EoL disassembly research? Specifically, (1) what are the potential applications developed by XR technologies in Industry 4.0-based disassembly operations and Industry 5.0-driven disassembly systems? (2) How can lean disassembly be aligned with the paradigmatic concepts of Industry 4.0 and Industry 5.0?
- What are the future research possibilities for the joint implementation of XR and lean in EoL disassembly under the impacts of Industry 4.0 and Industry 5.0? How can they favour the future of EoL disassembly planning?

1.3 Research objectives

This study is designed to focus on the exploration of EoL disassembly planning, rather than an abstract industrial scenario. The objectives of this thesis are as follows :

- To investigate existing academic research and characterize the current state of the art of EoL disassembly planning in the context of Industry 4.0 and Industry 5.0.
- To gain a deeper understanding of the theoretical underpinnings and review the evolutionary vein of industrial XR applications, digitalized lean management, Industry 4.0, and Industry 5.0.
- To identify future research possibilities, this study derives a decision-support agenda in Industry 4.0-based disassembly systems and develops an integrative framework in Industry 5.0-driven disassembly systems, both integrating XR and lean.

1.4 Organization of the thesis

The remainder of this study is structured as follows. Chapter 2 provides an overview of the research profiling of EoL product disassembly planning, Industry 4.0, Industry 5.0, XR, and lean. Chapters 3 and 4 introduce the two contributing articles, addressing the emerging gaps and deriving the potential integration of the association under Industry 4.0 and Industry 5.0, respectively. Lastly, conclusions are outlined in Chapter 5.

CHAPITRE 2 RESEARCH PROFILING AND RESEARCH CONTRIBUTIONS

Considering that the entire research is supported by two critical review papers to derive the potential association of XR and lean, this chapter presents the detailed organization and concludes the research profiling of all directional, paradigmatic, technological, and managerial elements in this study. It then discusses the barriers and issues, as well as the main contributions.

2.1 Research profiling

2.1.1 First article : XR–lean disassembly driven by Industry 4.0

To gain a view of the real industrial scenario, this article sets EoL aircraft as the research object. The recovery and remanufacturing of decommissioned aircraft represent potential circular business opportunities. Moreover, retiring aircraft is a complex and high-precision electronic product, requiring gradually systematic recovery management by enterprises. Previous scholars [17–19] have elaborated on the disassembly research of aircraft, and EoL aircraft management has been an independent research area since the 2010s [17]. This article starts from introducing sustainable management of the aviation industry and aircraft decommissioning processes, and investigate the current state of the practice of disassembly planning to unlock more transformative opportunities for XR applications and lean implementation.

2.1.2 Second article : the association of XR and lean with the inception of Industry 5.0

Industry X.0 is understood as a significant industrial evolution that encompasses the journey from proposing a core visionary idea to characterizing viable manufacturing advancements [20]. While the initial three Industrial Revolutions have already faded away, Industry 5.0 and Industry 4.0 are coexisting, and Industry 4.0 has not been replaced. Pursuing the aims of the essential societal needs, value, and responsibility are revealed in Industry 5.0 scholarly literature. Industry 5.0 complements the Industry 4.0 by achieving societal goals beyond jobs and growth [7]. The emergence of Industry 5.0 is a natural response rather than an accident. Standing on an unbiased ground to Industry 4.0 and Industry 5.0, XR-lean integration is reframed to discuss the possible applications in this article.

2.2 Barriers and issues

2.2.1 Disassembly planning at the end of the product life

Disassembly planning is known as a non-deterministic polynomial (NP)-hard optimization problem [21]. There are two factors hindering the optimization of disassembly planning : (1) the coexistence of multiple complexities, such as compulsory environmental and ergonomic constraints; (2) high-level uncertainties, such as global marketing demand, product quantities, qualities, and operating costs. Incomplete information of a product throughout its lifecycle may cause increased difficulties. Importantly, the difficulties can be significantly increased when disassembling multiple products, particularly complex assemblies consisting of numerous components. Additionally, each EoL product should have its own tailored disassembly plan, and most disassembly tasks are still carried out manually [22]. Given the need to promote the disassembly process and reduce complexities, disassembly planning has been a critically researched area in manufacturing. To uncover areas where techno-functional initiatives and tools could facilitate the disassembly planning in the context of Industry 4.0 and Industry 5.0, considerable critical attention should be given.

2.2.2 Transitioning from Industry 4.0 to Industry 5.0

Despite the clear benefits of developing Industry 4.0 thinking and applications in manufacturing and supply chains, research with a focus on disassembly planning of EoL products is under-explored. In the context of Industry 5.0, the challenges are even more severe. Both in practice and academic research, the current exploration of Industry 5.0 is still in an immature stage. Besides the lack of available knowledge regarding Industry 5.0 in the disassembly planning context, the existing authoritative literature on Industry 5.0 is insufficient, and the systematic introduction of Industry 5.0 has not been extensively explored [23].

2.2.3 Theory-driven derivation for the association of XR and lean

Less is known about the current literature on the benefits of joint implementation of XR and lean in the field of EoL disassembly planning. The limited literature available has a narrow scope. State-of-the-art research requires consistent knowledge about how XR and lean can jointly implicate disassembly planning under Industry 4.0 and Industry 5.0. The previous studies lack insight into the transformational adjustments of XR in parallel with the transition from Industry 4.0 to Industry 5.0. The research pathways of lean management to accommodate the design of disassembly systems for sustainable performance remain to be surveyed in Industry 4.0 and Industry 5.0.

2.3 Contributions

This thesis provides two main significant original contributions through articles, as described below.

The first contribution focuses on developing a content-based systematic literature review to explore the joint integration of XR and lean in EoL aircraft disassembly planning, then deriving an efficient and innovative EoL decision-support agenda, "Smart Disassembly Sequence Planning (SDSP)," for complex EoL products in general. Industry 4.0 represents the starting point of this contribution, and one of the major aims of the first article is to facilitate the elaboration of Industry 4.0 transformation. Similarly, the proposal of SDSP was accomplished through Industry 4.0 initiatives. Since much of the work published so far has concentrated on developing algorithms for the optimal sequence of disassembling, mathematical approaches may not be the best solutions to deal with the diverse nature of EoL disassembly preparations and operations. However, uncertainties in the EoL products and the implications of technological adoptions are unresolved issues that need to be addressed. Therefore, one key point of the first contribution is to enrich the literature about technology-assisted disassembly under Industry 4.0. In accordance with the pertinent literature on XR-assisted disassembly planning, collaborative XR-lean applications, and EoL aircraft management, the first article offered the first review of XR-lean-enabled disassembly planning. To fulfill the theoretical advancements of the review, the first contribution also includes proposing an agenda to enable future researchers to explore more correlations between XR and lean for sustainable manufacturing.

The second contribution consists of reviewing the opportunities and challenges of implementing the joint integration of XR and lean into EoL disassembly planning within Industry 5.0. Because of the core character of Industry 5.0, human-centricity, the second contribution centers on fulfilling the theoretical advancements of human-oriented disassembly planning. As a new industrial revolution, Industry 5.0 is attracting increased attention. This study also advanced the directional background for EoL disassembly while still focusing on core enablers, XR and lean. In the face of the technological stack activated in both Industry 4.0 and Industry 5.0, XR was also the primary techno-functional focus in the second article. XR technology includes wearable display devices and the prerequisite of user-centric experiential design in application development. Moreover, this article pointed out that lean also concerns the role of human safety and well-being. However, very few studies look into the issues of EoL disassembly from the perspective of Industry 5.0, particularly with the same integration of XR-lean as in "Article 1". Therefore, the second article offered the first review seeking the effective integration of XR with lean under the impact of Industry 5.0. Since Industry 5.0

scholarly literature is still in its infancy, the connotation of Industry 5.0 was also discussed in the second article. Therefore, the second article also helps reduce the vague viewpoints of Industry 5.0 by exploring a sustainable sector with a sharper focus, disassembly planning. The second article indicated that the convergence of XR and lean is potential in EoL disassembly planning in both Industry 4.0 and Industry 5.0, and the associated integration of XR and lean is necessary in EoL disassembly. Finally, the second article proposed a tailored framework for Industry 5.0-driven disassembly planning with supportive and assistive XR and lean. The summary of main contributions is presented Figure 2.1.

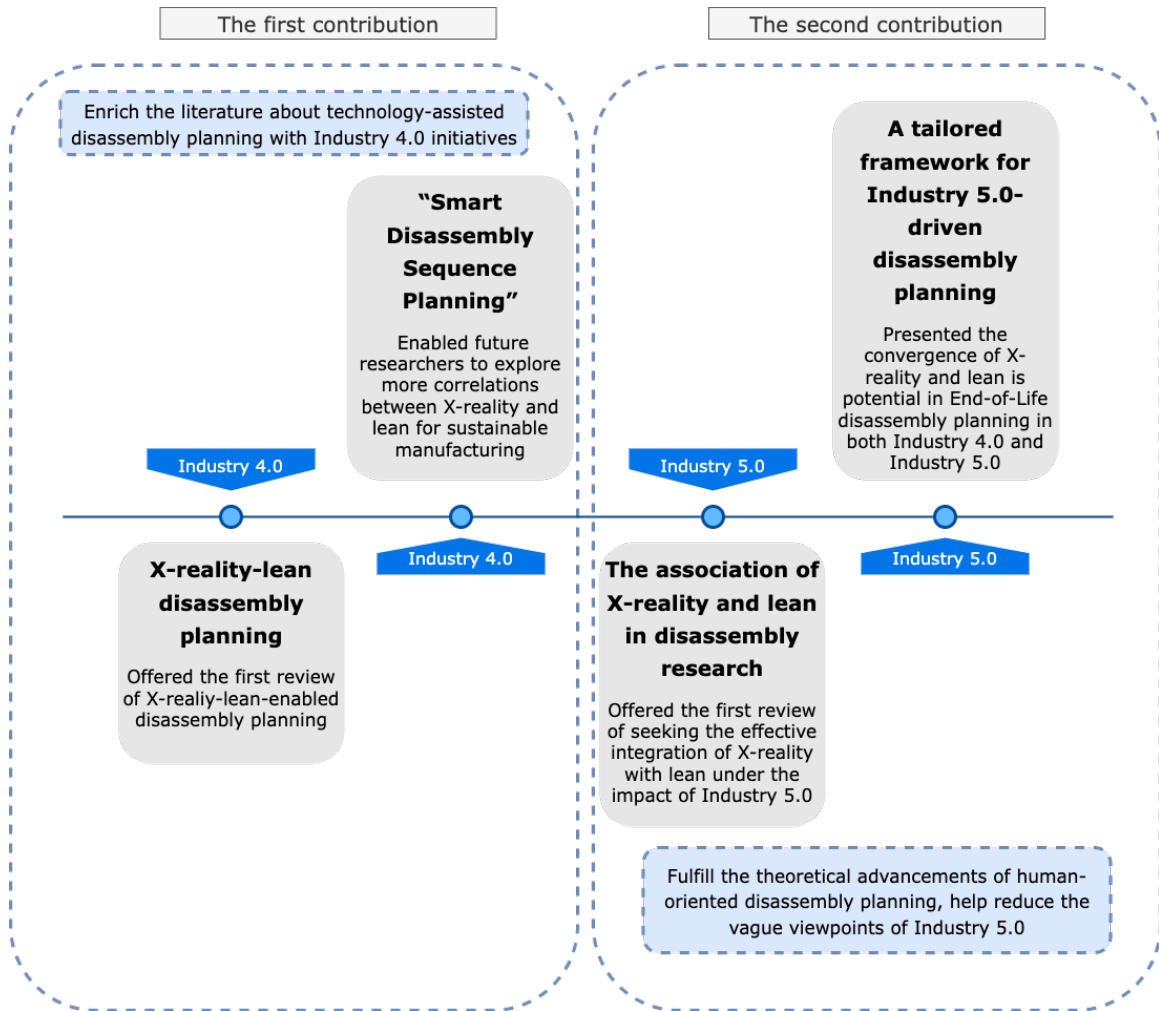


FIGURE 2.1 The summary of main contributions

CHAPITRE 3 ARTICLE 1: INTEGRATING X-REALITY AND LEAN INTO END-OF-LIFE AIRCRAFT PARTS DISASSEMBLY SEQUENCE PLANNING : A CRITICAL REVIEW AND RESEARCH AGENDA

This chapter presents a systematic literature review focusing on integrating X-reality technologies and lean management into the disassembly planning of end-of-life products (aircraft) under the impact of Industry 4.0. The manuscript contained in this chapter was co-authored¹ with my supervisor Dr. Samira Keivanpour, and my co-supervisor, Prof. Daniel Imbeau. I am the first author and the corresponding author. The manuscript was published in the journal The International Journal of Advanced Manufacturing Technology.

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1. **Author contribution** Yinong Yang : writing original draft, conceptualization, methodology, investigation, visualization, writing—review and editing, and formal analysis. Samira Keivanpour : supervision, conceptualization, project administration, and review. Daniel Imbeau : supervision and 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 implications and stakeholders' benefits. Among the Industry 4.0 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 Industry 4.0 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, Industry 4.0, 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, Smart disassembly sequence planning (SDSP), X-reality (XR), Lean

3.1 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 [17]. EoL aircraft management refers to the whole process planning of withdrawing, disassembling, and dismantling a soon-to-be-retired aircraft [24,25]. 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 [26]. 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 [27]. Recently, it was determined that 90% of the used serviceable content of soon-to-be-retired aircraft could be recycled or reused [26]. 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 [28]. Since retired aircraft are not allowed to fly again, high-volume parking and storage demands can cause financial waste and environmental risks [26]. Uncertain external factors (e.g., financial crises, oil prices, and the pandemic) have already caused the number of decommissioned aircraft to fluctuate considerably [29]. Taking the present waste and unpredictable risks into account, improving the efficiency of treating incremental EoL aircraft is an urgent need [30].

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 [26,27]. As the first and most challenging operation in the EoL stage, the disassembly process involves the systematic separation of all valuable components [22]. “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 [31]. 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 [6]. 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 technology research over the past decade, this trend has created the technological push factors for traditional manufacturing. If any assistive Industry 4.0 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 Industry 4.0 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 [8]. 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 three dimensional (3D) position detection of hardware and virtual interfaces [14]. 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 [32,33] and VR vocational training [34]. 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 [3]. 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 [35]. Waste (or Japanese equivalent “MUDA”) is conceived as the

paramount role in lean [36]. 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 [36, 37]. Lean covers a set of techniques and principles for striving towards operational excellence in the customer-pull demand context [38]. 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 [39]. 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, Industry 4.0 and lean, has provoked extensive discussion in academia [3]. 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, Industry 4.0, 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 Figure 3.1.

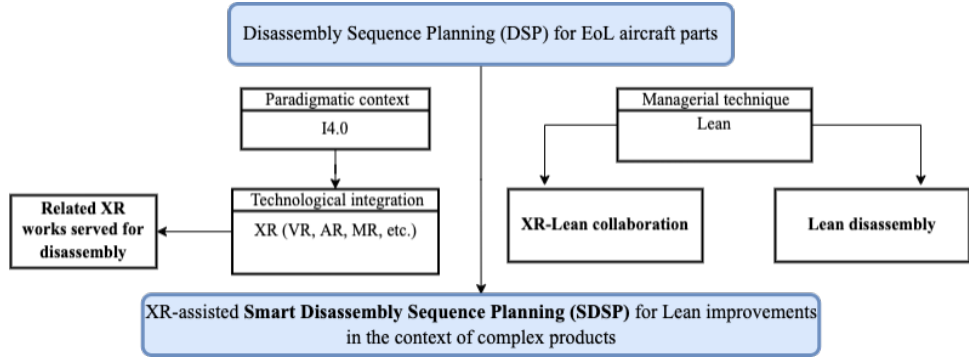


FIGURE 3.1 The transitional information flows

3.2 Theoretical background

3.2.1 EoL aircraft management

3.2.1.1 High-value aviation-purpose parts

BIPAD concluded with a list of typical high-value parts (shown in Table 3.1). 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 [26]. The engines are even more valuable than the entire retired aircraft in certain situations [26]. 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 [29]. Furthermore, IATA listed other high-value components, including avionics, environmental control systems (ECS), safety equipment, wheels, and brakes [26].

3.2.1.2 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 Figure 3.2) : (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 recovery work cluster (disassembly operations and disassembled parts’ arrangements) is circled in the dashed black frame in Figure 3.1 [40]. The general recovery and reuse procedures (disassembly and dismantling) are placed in the green zone.

TABLEAU 3.1 The typical high-value parts listed in BIPAD (the source of information : BIPAD)

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

Disassembly and disassembled parts Owing to the aviation-purpose character, disassembly is deemed “an aerospace activity” in the business context [26]. In the exploration of the additional features contained in the “disassembly” step, [26] 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 Figure 3.3, [26] 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. [41] 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 3.2.1.1.

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 [26,40]. As presented in Figure 3.4, 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

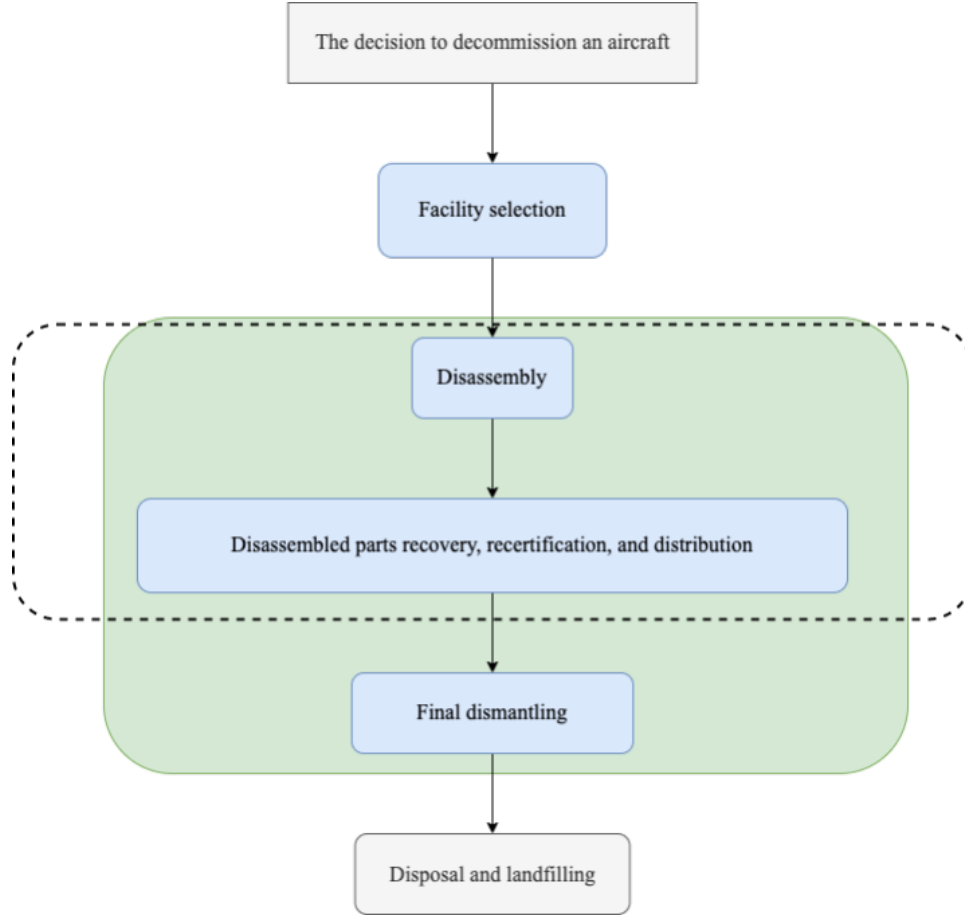


FIGURE 3.2 Key activities in EoL aircraft management (the source of information : BIPAD)

are not undertaken by any approved aircraft maintenance organizations. The remarketing paths mentioned by [26] (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 [26]. 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 [26].

3.2.2 DSP of complex products

Disassembly is a labor-intensive process in most application domains [42]. The “disassembly” step is a vital process for any EoL options or treatments [5, 43]; thus, this is the thematic research focus of this review. As a direction warranting deeper investigation within disassem-

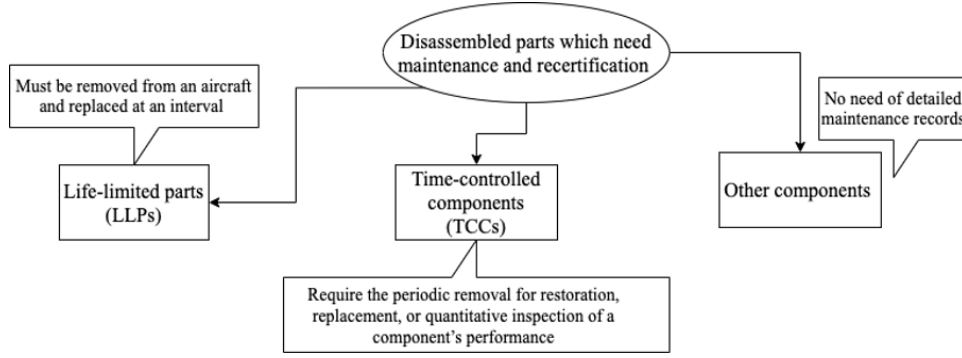


FIGURE 3.3 The categories of disassembled parts (the source of information : BIPAD)

bly science [5], DSP outcomes are critical for the entire recycling chain network [22]. 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 [22]. 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 [5, 44, 45], the general DSP solution spans three distinct steps : (1) disassembly process/type/ level identification, (2) disassembly information modeling, and (3) sequence decision analytics.

Reference [1] defined the disassembly process/type/ level identification as the “disassembly mode” selection. Similarly, [5] 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 [5]. Moreover, to minimize the adverse effects on labor time, parallel disassembly planning methods could be utilized in large, complex EoL products [1]. The disassembly level entails full

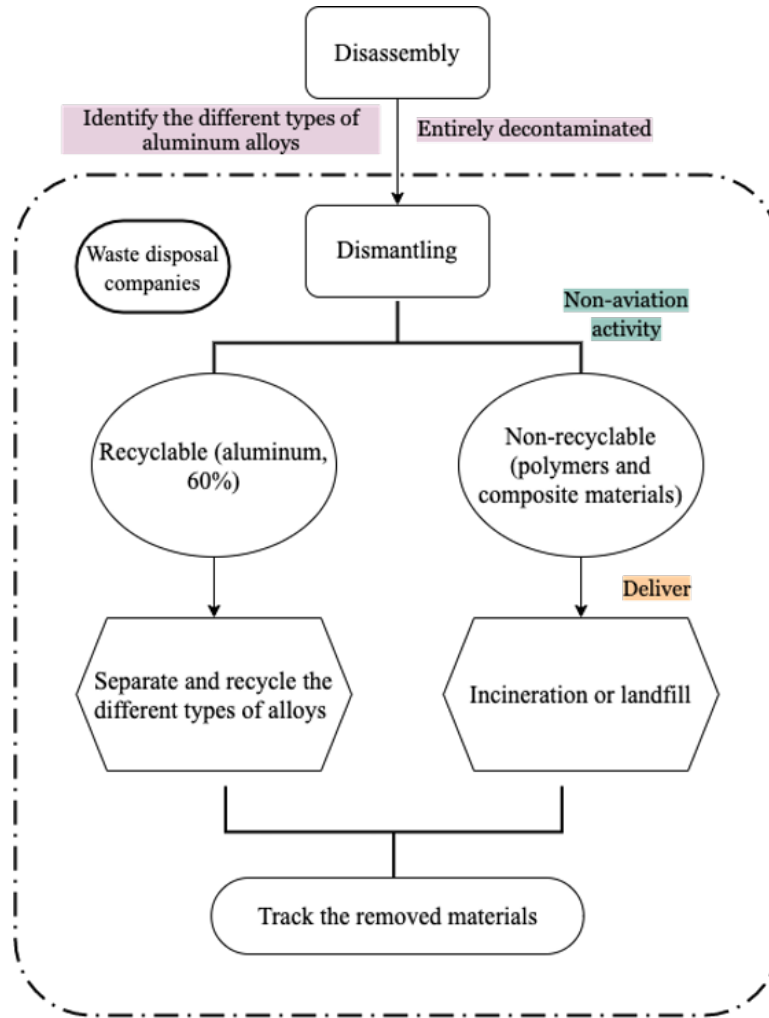


FIGURE 3.4 The dismantling process (the source of information : BIPAD)

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 [46]. 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 [1], as presented in Table 3.2 : (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

TABLEAU 3.2 Disassembly information modeling methodologies for EoL product representation (the source of information : [1])

Category (formats)	Description
1- Graphs	<i>Targets :</i> (1) Disassembly process visualization (2) Inclusion of disassembly details (such as disassembly time and tool) <i>Representative methods :</i> (1) AND/OR graph ; (2) Hierarchical graph ; (3) Liaison graph ; (4) Contact state graph
2- Petri net	<i>Targets :</i> (1) Provide detailed descriptions of how the parts are connected (2) Simplify and generate the reachability graph effectively <i>Representative methods :</i> (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	<i>Target :</i> (1) Minimal manual intervention <i>Representative methods :</i> (1) Disassembly interference matrix (2) Multi-direction matrix (3) Disassembly transition matrix

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 [6]. 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 [5]. 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 [47]. 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 [5]. 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 [48, 49]. 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 Industry 4.0 technologies.

3.2.3 Industry 4.0, XR, and lean

3.2.3.1 Industry 4.0

Industry 4.0 refers to the fourth industrial revolution and has been discussed frequently in recent research [50]. Since Industry 4.0 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 [51]. The tendency to apply information and communication technology (ICT) has already been embodied in practices that favor Industry 4.0. The progress driven by computing power and software efficiency highlights the advances of Industry 4.0 [52]. In *Green Supply Chain Management*, a book by [53], a solution involving green information and communication technologies (GrICT) was identified : GrICT systems could support operational, tactical, and strategic decision-making processes [53]. The available GrICT solutions comprised various Industry 4.0 technologies. Moreover, GrICT aimed to “make ICT solutions for managing green practices” in most engineering fields. In the current Industry 4.0 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 [53]. In essence, the integration of hybrid Industry 4.0 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 Industry 4.0 technologies, the proven implications require demonstration. Essentially, the scholastic content of real-life Industry 4.0 applications' evaluation and examination is minimal. The literature has shown that some relevant “4.0” terms have been created, such as “Disassembly 4.0” [54], “Aviation 4.0” [55], “Lean 4.0” [56], and

“Remanufacturing 4.0” [57]; 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 Industry 4.0 technologies are rarely involved in the disassembly process [58]. As the adoption of Industry 4.0 technologies has restricted adaptability challenges (e.g., unacquainted skills, information overload, and investment limitations), there is a need to investigate detailed Industry 4.0 technologies for the DSP of EoL aircraft parts.

3.2.3.2 XR

XR represents a taxonomy of “realities” [59]. 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 [60]. 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 [61]. 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 multisensory tracked controllers to experience the programmed activities with low-latency motions [62]. 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 [63]. 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 [64, 65]. 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 [66–68]. 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 Figure 3.5.

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 [69], interactive video games and playable media [70], architecture and construction [71], aerospace [72, 73], marine studies [74], and medicine [75]. Built on the swift development of continuously upgraded

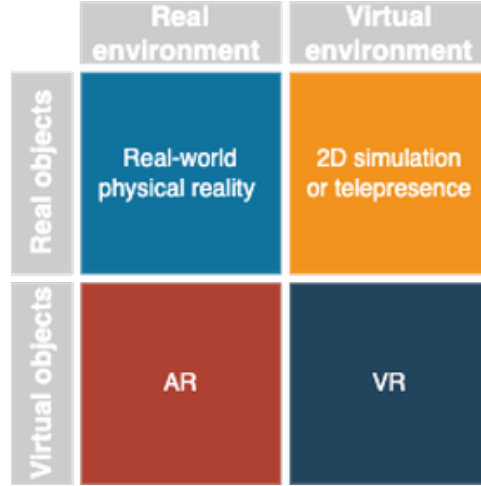


FIGURE 3.5 The general classification based on the objects and the environment

software and ergonomic hardware, XR is not limited to characters as a visualization tool or display technology [76–78]. Grounded in a human-centric mindset, VR is a countermeasure because the artificial virtual environment can create dangerous job-shop scenes for training operators [79]. 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, [80] 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 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, [81] 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 [82], 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 [79]. For instance, [83] 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 [84]. 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 [85]. “Cybersickness” has been a marked drawback since the adoption of XR became a possibility [84]. 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 [86]. 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 [87]. The weights of HMDs, glasses, and other relatively clumsy devices can also cause experiential distraction [86]. 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 [60].

3.2.3.3 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 [88]. From the operations point of view, lean management is particularly relevant for removing of non-value-adding operational practices to enhance natural resource efficiency [89]. 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 [88, 89]. Previous studies have investigated the adoption intention of lean in circular practices and sustainable manufacturing [88–91]. Given the dominance of lean, lean remanufacturing has recently gained incremental attention in academic research [90, 92], with lean disassembly distinguishing it-

self 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 Industry 4.0 phenomenon has been established, the innovative adoption of emergent technologies is anticipated for the continuous improvement of operational effectiveness [93]. The deployment of Industry 4.0 technologies is expected to bring favorable impacts through purposeful fulfillment of transformational digitalization, enabling smart manufacturing and smart decision-making [94]. However, despite the recent maturity of Industry 4.0 technologies, remanufacturers still lack a comprehensive understanding of how Industry 4.0 technologies can affect the established lean disassembly. Previous literature has constantly argued that lean has evolved to coexist with information-driven technologies [39], and lean and Industry 4.0 are interconnected due to their commonalities in operational performance [95]. Recent studies have focused on two directional perspectives : lean is the basis of Industry 4.0, or Industry 4.0 improves the effectiveness of lean operations [3]. The lean-Industry 4.0 transformation is intended to create high impact and immediate value during product-process management. The integration of concrete Industry 4.0 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 Industry 4.0-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 [96] ; (2) how industrial XR can leverage its capabilities (e.g., multidimensional information-sharing and visualization) to enable a lean disassembly system [93].

In addition to the practical advice on the process for improving productivity, the workforces

behind the tools are crucial factors for successful lean implementation [97]. 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 [97]. When the occupational health and safety responsibility is addressed at scale, physical and psychological human aspects of employees are accumulated issues [97]. To recapture the value of the workforce, previous scholars (e.g., [98] and [99]) 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, Industry 4.0, 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 Industry 4.0-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?

3.3 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 [93]. 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.

3.3.1 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 3.2, 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, Figure 3.6 shows the pipeline of the first-stage screening strategy employed in WoS ; a total of 1655 journal articles were listed.

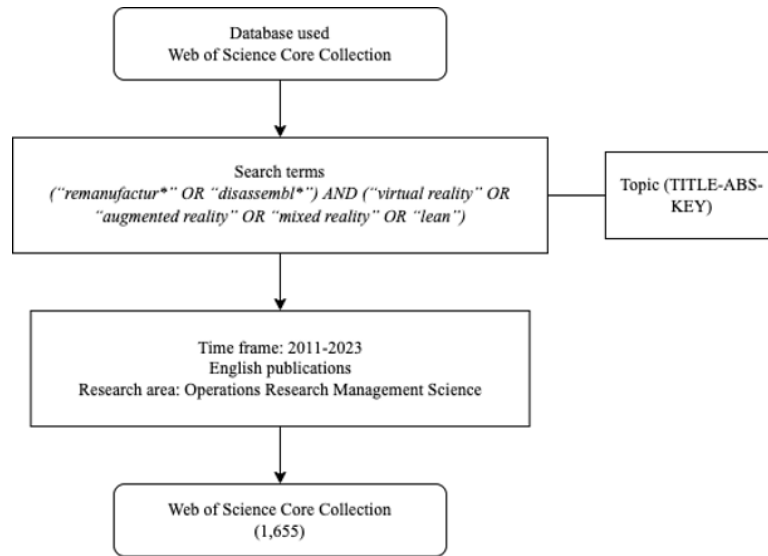


FIGURE 3.6 The pipeline of the screening strategy for the WoS database

The publication year and journal distribution charts are illustrated in Figure 3.7 and Figure 3.8, respectively. While Figure 3.7 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 inspired by Industry 4.0. As shown in Figure 3.8, the top ten journals were extracted to analyze the publishing distribution : the existing articles were mainly publi-

shed 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.

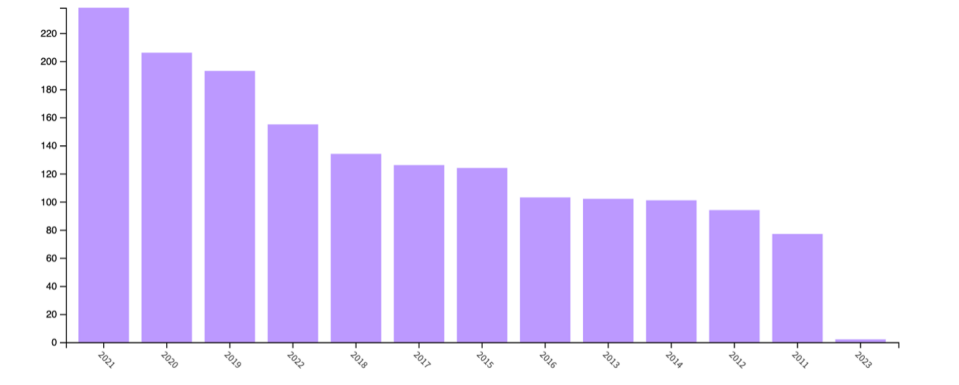


FIGURE 3.7 Distribution of relevant articles by year of publication

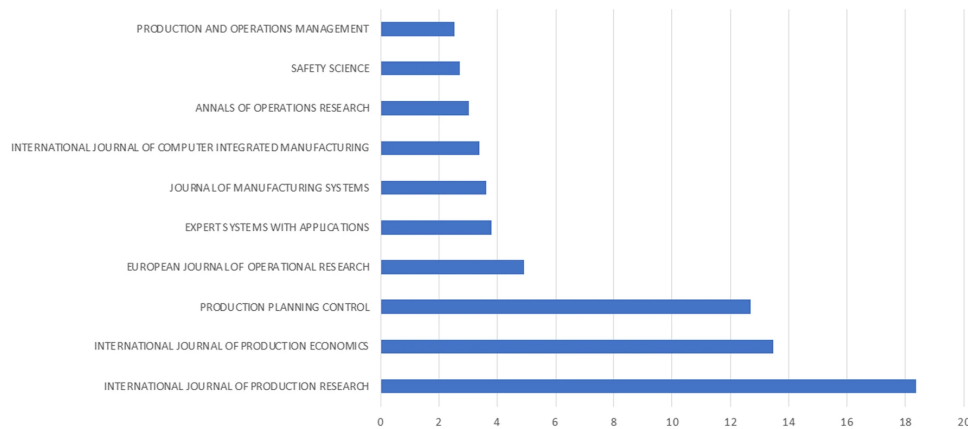


FIGURE 3.8 Distribution of relevant articles by journal outlet

3.3.2 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, [100], 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 Industry 4.0 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 :

3.3.2.1 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 : [101] and [102]. Based on their critical reviews, these two papers designed and developed Industry 4.0-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 Industry 4.0-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 3.3, all the key concepts of this study were segmented and listed as four groups. To minimize the subjectivity, the consideration 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.

TABLEAU 3.3 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

3.3.2.2 Literature search, screening, and eligibility checks

Table 3.4 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.

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 3.5, the entire search process involved two steps : in the first step, based on the four groups’ representations listed in Section 3.3.2.1, 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

TABLEAU 3.4 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

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.

TABLEAU 3.5 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

The flowchart revealing the keyword combinations' search steps is presented in Figure 3.9. A total of 194 relevant 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.

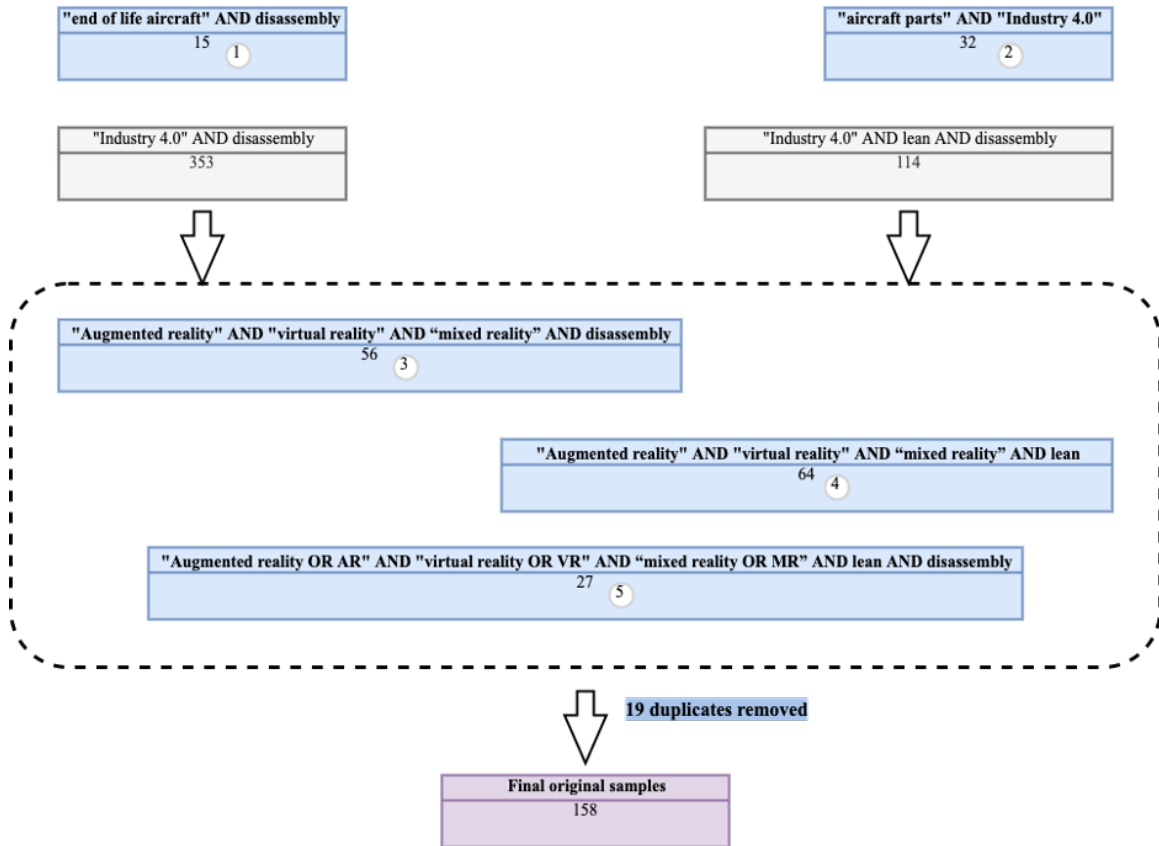


FIGURE 3.9 Flowchart of the process of the literature search and selection

3.3.2.3 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 [103]. 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 [104]. With regard to the search strings in Section 3.2.2.2, 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 Figure 3.10. 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 Industry 4.0. 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 [103,104]. In Figure 3.10, 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 3.6. The keywords were organized and examined using VOSviewer, and the featured function understanding could be less obfuscated in the literature.

TABLEAU 3.6 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				

Table 3.6 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.

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 Figure 3.10. As XR and other Industry 4.0 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.

3.4 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.

3.4.1 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

For DSP, [105] 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 [105]. However, this arrangement could be close to the dismantling stage (see Section 3.2.1.2) 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 [105]. Afterward, the “disassembly factsheet” was made from operational information (e.g., operational time and number of fasteners) for the final evaluation. Similarly, [106] 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, [19] 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 [19]. 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 [19] 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,” [55] presented this Industry 4.0-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 [55]. This content was mentioned in a new book, *Intelligent and Fuzzy Techniques in Aviation 4.0*, by [107], 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 [6]. 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 3.7 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 Industry 4.0 initiatives, there has been a considerable focus on technology-driven disassembly planning, originating from the aforementioned “computer-aided disassembly planning” [48]. A new “computer-aided disassembly planning” should be advanced with the aid of cyber-physical human–machine collaboration.

3.4.2 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 crossapplication approach, the final samples reported that XR-related maintenance and assembly applications comprised a considerable portion of selected

TABLEAU 3.7 Related findings for EoL aircraft parts disassembly planning

References	Relevant contributions	Selected case
[108]	The standard data source Aircraft Maintenance Manual for disassembly tasks	
[105]	Four EoL airframe “disassembly alternatives” and a feasibility analysis based on the disassembly difficulty	A real jet airliner carcass
[106]	Eight different disassembly/dismantling strategies under the project “Process for advanced management and technologies of aircraft end-of-life”	
[19]	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

literature [85]. 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 [60, 109], 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.

3.4.2.1 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 [110]. 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 [111]. 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 [110]. For disassembly and assembly operations, the real world can be enhanced, and the targeted part can be detected properly in real time.

Reference [33] 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 [33]. 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 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) [33]. Furthermore, the computational design and development processes were left out. This paper only mentioned the names of related programming techniques and languages. [32] 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 [32]. 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, [112] 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 [112]. 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 [112]. 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 [112]. 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. [113] 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 [113]. Regarding AR-assisted disassembly planning for the aviation purpose, [6] 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 3.8 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.

3.4.2.2 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 [114]. 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 [65, 115]. 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 [116]. 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, [117] examined the advances in ICT and highlighted the

TABLEAU 3.8 Recent works of AR-assisted disassembly

References	Framework	Application	Perspective	Optimization	Tools	Case
[33]	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
[112]		Augmented reality Disassembly Evaluation Tool : produced the product representation through marker-less tracking and detection and then assisted information modelling		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
[113]		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
[32]		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 third- hand assembly
[6]			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

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 connected the colored nodes. To better visualize the disassembly alternatives from the disassembly graph, [117] 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 [118]. Notably, the primary focus of this paper became the uncertainties during disassembly operations, and [118] 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 me-

thods 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, [119] 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 [34], the on-site operational uncertainties also included the faults caused by unskilled labor because of incorrect memory and lack of experience. Moreover, [34] 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 [34]. Because of this demand, the "UnityWebRequest" system was applied from the "UnityEngine. Networking" document [120]. 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 [34], a cloud server, the connection between Petri nets and graphic neural networks, and a stable immersive experience were the main challenges. Table 3.9 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.

3.4.2.3 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. [68] 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, in-

TABLEAU 3.9 Related technical work of VR-assisted disassembly operations

Literature	Outputs	Optimization	Tools	Case
[117]	An interactive VR Juggler-based project examining the disassembly graph	Node-based hierarchical graph	VR Juggler (device : Nintendo Wii Remote)	Six-piece Burr puzzle
[118]	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
[119]	A virtual 3D landing gear disassembly modeling and animation system		Unity3D, iTween, 3ds Max	Landing gear
[34]	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

put-output, and immersion). The most popular understanding that numerous researchers have agreed upon is the notion of a "reality-virtuality continuum" [66, 68]. MR has been placed on this continuum from completely physical environments to computer-generated immersive ones [66, 67]. In the present study, MR is described as an agile vision that is not yet an established application perspective. For example, [121] 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 [121]. 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.

3.4.3 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, Industry 4.0 could not displace the philosophical lean. However, the evidence for the joint application of lean and Industry 4.0 technologies remains insufficient. The majority of the previous studies presented the proof-of-concept correlations between lean principles and Industry 4.0 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 Industry 4.0 technologies—or lean tools and Industry 4.0 principles—could be reinforced by each other [2,122]. 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 [96], lean could be a rational starting point for implementing Industry 4.0-generated changes to produce performance benefits. [122] defined the term “Lean 4.0” and, in terms of the correlation, determined that Industry 4.0 could exert a compensatory effect on lean’s shortcomings. [122] also stated that lean processes were the basis of feasible Industry 4.0 technology implementation. In particular, VSM 4.0, VM 4.0, and Poka-yoke 4.0 were mentioned because these rely on realtime 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, [122] 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 3.10 summarizes these potential correlations by [122]. From a diverse perspective, [3] categorized the implications of Industry 4.0 technology competence for lean principles based on four-level capability degrees. The four levels of Industry 4.0 technologies’ competences that they used had been proposed by [123] : 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 3.11. Notably, for AR, the “monitoring” level was the only matched Industry 4.0-based capability when influencing various lean principles. The illustrated lean principles were jidoka, people and teamwork, and foundations. Although the examination visions of [3] and [122] differed, their findings were similar due to the inherent connections. As Table 3.11 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 [124] presented, the visual techniques were ubiquitous and valuable factors, and they reflected the evident features of lean. Similarly, [125] 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 Industry 4.0 and lean, but VR and MR are also powerful techniques that can assist reconfigurable monitoring systems. Furthermore, the control, optimization, and autonomy impact levels could be explored when applying XR technologies.

TABLEAU 3.10 The potential correlation between “Lean 4.0” and XR (the source of information : [2])

XR	Lean 4.0	Potential correlation
The role of a visualization tool	VSM 4.0 VM 4.0 and Poka-yoke 4.0	The remote controlling of real-time value streams 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

TABLEAU 3.11 Capability level (monitoring) of AR impacting Lean principles (the source of information : [3])

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

All the major XR–lean research showcases were focused on the training performance improvement of individual operators, especially in architecture, engineering, and construction. [126] 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 [63], the industrial XR use cases could involve stakeholder engagement, design support, and management support in addition to training. For example, [18] 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 [18]. 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.

3.5 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. [127] and [128] 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 Industry 4.0, 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 [129]. 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.

3.5.1 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 Figure 3.1. 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 Industry 4.0 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 [130]. 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 Industry 4.0-based disassembly, the relevant term “smart disassembly” only occurred once in [131]. 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 [131]. 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 Industry 4.0 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” [132], “smart manufacturing” [133], and “smart remanufacturing” [134], that were driven by Industry 4.0. “Smart” can be a core competency involved in the development of technological advances. To launch Industry 4.0 initiatives, SDSP should leverage the full potential of laying Industry 4.0 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 Industry 4.0–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.

3.5.2 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 3.12.

3.5.2.1 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 [130]. Howe-

TABLEAU 3.12 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 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

ver, 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 3.3.2.3, we learn that circular economy is crucial in remanufacturing because it promotes circularity of network flows [134]. 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 [135]. 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 Industry 4.0, 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 [135]. 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 [63]. 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.

3.5.2.2 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 [63]. 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 [63]. 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" [136] perspective could be an applicable starting point due to the multi-stakeholder engagement journey in the general remanufacturing organization.

3.5.2.3 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 Industry 4.0 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 Industry 4.0 technologies in theory and practice, and the collaborations among various Industry 4.0 technologies have gained enough attentions [102]. However, utilizing overarching Industry 4.0 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 [8]. Considering the previously discussed challenges in "XR content", the engagement of IoT devices [24] 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 [63]. 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 Industry 4.0, Industry 5.0 connects a sustainable and human-centered paradigm and Industry 4.0 technologies, even though it might be a premature concept [20]. 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. "XR experiences" 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.

3.6 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 Industry 4.0-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 Industry 4.0. 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 Industry 4.0 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.

CHAPITRE 4 ARTICLE 2: THE FUTURE OF DISASSEMBLY PLANNING : A CRITICAL ASSESSMENT OF INDUSTRY 5.0, LEAN, AND X-REALITY

This chapter presents a systematic literature review and framework analysis focus on the integration of Industry 5.0, lean, and X-reality for human-centric disassembly management at the end of product-life. The manuscript contained in this chapter was co-authored¹ with my supervisor Dr. Samira Keivanpour, and my co-supervisor, Prof. Daniel Imbeau. I am the first author and the corresponding author. The manuscript was submitted to on August 4, 2023.

1. **Author contribution** Yinong Yang : writing original draft, conceptualization, methodology, investigation, visualization, writing—review and editing, and formal analysis. Samira Keivanpour : supervision, conceptualization, project administration, and review. Daniel Imbeau : supervision and review.

The Future of Disassembly Planning : A Critical Assessment of Industry 5.0, Lean, and X-reality

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Abstract Disassembly is a key step in most end-of-life (EoL) product recycling strategies. Due to increasing economic motivations and environmental concerns, traditional disassembly entails paradigm shifts and the integration of digital technologies to support process planning. Industry 5.0 and X-reality (XR) are notable representatives in this context. With the extension of societal transformation, Industry 5.0 aims to build a human-technology or human-machine companion to emphasize the importance of human safety and well-being in tremendous industrial evolutions. Industry 5.0 can promote the harmonious collaboration of humans, operations, and machines within the disassembly system. XR encompasses virtual and augmented reality technologies and addresses the human-reality gap in virtual worlds. By leveraging XR to simulate and visualize product information and experimental operations, disassembly planning can be facilitated. However, the roles of Industry 5.0 and XR in EoL product management remain under-explored, and the existing literature has neglected the possibility of linking them with lean. This paper first reviewed the extant literature on the potential association of Industry 5.0, lean, and XR for disassembly planning, offering one of the first research articles to highlight current trends. This paper further presented the preliminary work by constructing a tri-dimensional framework to combine three paradigms of human-centric, smart, and lean in the disassembly domain under Industry 5.0. Our findings not only underline the emerging gaps and the unexplored areas but also offer a valuable framework to advance digital disassembly transformation.

Keywords Disassembly, End-of-life (EoL) product, Lean management, Industry 5.0, X-reality (XR)

4.1 Introduction

As manufacturing businesses continued to improve economic performance by embracing Industry 4.0, a new industrial revolution emerged, known as Industry 5.0. Industry 5.0 is an upcoming human-centric and society-centric paradigm [104]. As of now, Industry 5.0 and Industry 4.0 are currently coexisting within the challenging global context. In 2021, the European Commission formally released a white paper titled “Industry 5.0 : Towards a Sustainable, Human-centric and Resilient European Industry”, which indicated the features [23] or three core values [7] of Industry 5.0 : human-centricity, sustainability, and resilience [137]. This represents the consensus of the European Union, similar to the concept of Industry 4.0 (Industrie 4.0) introduced by the German government. With the increasing expectations of sustainability enhancement, environmentally and socially aware manufacturing organizations are experiencing significant changes under the impact of Industry 5.0.

Especially in the context of end-of-life (EoL) product management, there are relatively few accounts in academic literature that have investigated the influence of Industry 5.0. In recent decades, efforts have been made in EoL product management to contribute to sustainability [138]. When a product approaches the end of its economic or operational life, recovering it to like-new conditions to close the loop of industrial components is more sustainable compared to newly manufactured products. By implementing remanufacturing processes (e.g., cleaning, disassembly, and dismantling), EoL product management can highlight the benefits of reducing manufacturing costs, redundancies in new production, the consumption of non-renewable resources, landfills, waste, and the adverse effects on the environment. As a business opportunity for product life extension, managing EoL product shows great promise with respect to economic, environmental, and social impact. To collect EoL products that will eventually be recovered as second-hand items, used products need to be systematically disassembled first [4]. Disassembly is an unavoidable step in EoL product recycling strategies and an essential part of waste management flows [5]. However, in traditional circumstances, disassembly is recognized as a labor-intensive and manual operation, and unplanned disassembling activity can easily be inefficient and uneconomical [4, 5]. Moreover, creating an optimal disassembly plan is challenging due to the coexistence of multiple complexities, such as compulsory environmental and ergonomic constraints, as well as high-level uncertainties (e.g., marketing demand, product quantities, structural information, and operating costs) [139]. The intrinsic and extrinsic challenges that EoL disassembly operations face involve improving sustainable performance while reducing potential health and safety dangers to people. Given these challenges, it is worth exploring whether Industry 5.0 is more readily applicable to EoL disassembly planning, and if so, how it can accelerate EoL product management to

improve sustainable development since its inception.

In line with previous research, incorporating digital technologies into industrial sectors has created opportunities for value generation and securing a competitive advantage [11,140]. The call for digital disassembly transformation is also driven by technological progress. X-reality (XR) encompasses various initiatives related to virtual-physical systems, which involve the latest advancements in wearable equipment and digital channels (e.g., cross-platform software) [141,142]. XR is a type of human interaction and recognition technology. In this study, the term “X” represents the functional attribute, and XR technologies encompass, but are not limited to, virtual reality (VR), mixed reality (MR), and augmented reality (AR) [8,65,143]. While XR has been extensively discussed in the existing literature on Industry 4.0, it can also be considered an important technological component of Industry 5.0 [12]. XR-assisted disassembly planning can be seen as a transformative process to thrive and grow digital fulfillment (Industry 4.0) solutions. Some studies [6,13,144] have explored the cooperation opportunities between XR and disassembly and have elaborated on the integrative roles of production simulation, visual reasoning assistance, and operational guidelines. The proposed study will emphasize the adoption of XR technology as the primary means to improve disassembly in the context of Industry 5.0.

By catering to the needs of integrating Industry 5.0 with its feature-specific XR technology, lean is underlined to engage and interact in disassembly management. Lean, as a term, originally drew its thinking strategies from the Toyota Production System of the Japanese automotive industry [3,145]. The aim of implementing lean is to eliminate any non-value-adding activities through productivity-enhancing tools, intrinsic thinking, and a customer-oriented organizational structure [13,17]. Lean thinking/principles and practices/tools have been extensively accepted and applicable in the manufacturing setting [146]. For instance, kaizen represents one of the fundamental lean principles that aims to achieve continuous and incremental improvements. Another well-known lean tool is value stream mapping (VSM), which involves documenting, analyzing, and improving the manufacturing process using flow diagrams [145,146]. Lean and Industry 4.0 share commonalities in terms of their goals, which include satisfying customer needs, and both approaches have analytical purposes focused on achieving superior productivity and flexibility [147]. Therefore, several studies [56,91,148,149]) have investigated the coexisting relationship between lean and Industry 4.0, highlighting lean as a relatively stable and established management approach for exploring new digital propositions. Overall, both in practice and in academic research, the relevance to humans can be observed in Industry 5.0, XR, and lean.

Under the premise that Industry 5.0 and lean can collaborate towards sustainability, the lack

of concentration is problematic [11]. Much of the published work has focused on abstract industrial subjects rather than a specific domain of EoL product treatment, such as disassembling and remanufacturing. Motivated by previous studies, it is an opportune time to examine the new competencies in disassembly research that have been upgraded by Industry 5.0. Additionally, a proper understanding of the adaptability and functions of XR in Industry 5.0 becomes paramount. Despite the potential significance of XR in computer-aided remanufacturing, research on Industry 5.0 with a specific focus on XR is limited. In other words, the past literature lacks insight into the transformational changes of XR in parallel with the transition from Industry 4.0. The research pathways of XR applications to accommodate the design and development of Industry 5.0 systems remain to be surveyed. Most importantly, the majority of earlier research lacked elaboration on how their collaboration is possible in EoL disassembly planning. The combined effects have scarcely been explored in past literature, rather than considering one or two elements at a time. To extend beyond the originally defined characteristics (human-centricity, sustainability, and resiliency) in disassembly areas, a tailored structure should be designed to present drivers, synergies, and conflicts among three elements.

To apprehend possible partnering arrangements, the purpose of this study is twofold. Firstly, this article aims to review the ongoing interactions among lean practices, human-centric XR applications, and smart EoL product disassembly based on the findings from the extant literature. Secondly, considering the current exploration of Industry 5.0 is still in an immature stage, there is a need to propose a potential integrated framework to discern the validation. The triangulation of Industry 5.0 (a human-centric initiative), lean (a productivity-enhanced management system), and XR (a technological enabler) is discussed. To explore the coordination along with other heterogeneous systems in real applications, a human-centric, smart, and lean (HSL) paradigm is proposed for explaining the triangulation. As a harmonious system, HSL represents the logical continuation of operating Industry 5.0 led association in disassembly. HSL can also reveal the shortcomings of the current Industry 4.0 systems. To the best of our knowledge, this theoretical research is the first study to review the possibilities of connecting Industry 5.0, lean, and XR in the field of EoL product disassembly. The analysis of the current literature focuses on answering the following research questions (RQs) :

- RQ1 : What are the present trends regarding the association of Industry 5.0 and lean paradigms in the context of sustainable manufacturing ?
- RQ2 : What are the potential directions and pathways for XR applications in EoL disassembly systems from an Industry 5.0 perspective ?
- RQ3 : What are the possible inter-relationships among Industry 5.0, XR, and lean ?
What are the future research possibilities in the integrated HSL paradigm ?

The remainder of this review is structured as follows. Section 2 comprehensively describes the research profiling of Industry 5.0, XR, and lean, providing a foundation for research studies and positioning. Section 3 explains the research questions and methodology employed in this study. Section 4 shows major review findings by summarizing and analyzing selected publications and presents the theoretical integrated HSL framework. Finally, section 5 provides concluding remarks for the entire review and discusses future research initiatives.

4.2 Overview of basic terminology

4.2.1 Disassembly planning of EoL product

During the EoL stage, disassembly operations are typically carried out first to recover the residual value of products and components for circular use [150]. Disassembly planning is known as a non-deterministic polynomial (NP)-hard optimization problem [13, 21]. From a research point of view, an effective disassembly plan entails a series of safe and time-saving tasks, resulting in organized and optimal sequences considering multifaceted factors and criteria [5]. The optimization objectives encompass processing time for disassembly preparation and operation (e.g., sequence planning, process optimization, and training), costs, steps, and tools, as observed in prior literature [151]. However, the highly uncontrollable variability in EoL product conditions can impede disassembly process planning [108]. Additionally, disassembly decisions may suffer from inaccuracies and inconsistencies in EoL information. The complexities can be significantly increased when disassembling multiple products, particularly high-precision electronic products. Consequently, a purely mathematical formulation may not always lead to the most practical decisions; instead, it can escalate computing complexity and inaccuracies during the disassembly process [5]. Besides, hazardous material removal is a crucial disassembling task during the EoL stage. In this manual operation, disassembly planning should consider the degradation of the health and safety of the operators, aiming for a human-centric collaborative system. Therefore, the current research on EoL disassembly planning encounters challenges in ensuring secure, economic, and ecological processes, resulting in a bottleneck in EoL product management. EoL disassembly planning requires advanced solutions to remain competitive in the setting of digitalization and sustainability.

4.2.2 Industry 5.0

Industry 4.0 remains one of the predominant manufacturing paradigms. However, there have been increasing discussions in recent scholarly work regarding the transition from Industry 4.0 to Industry 5.0. Publicly introduced in 2011, Industry 4.0 was promoted to apply arti-

ficial intelligence and cyber-physical collaborations to transcend traditional manufacturing and production systems [23,148]. Techno-centric Industry 4.0 aims to foster relatively smart manufacturing for improving customization and effectiveness. The conceptual and practical pillars of Industry 4.0 are supported by emerging technologies (e.g., AR, VR, MR, digital twin (DT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI), internet of things (IoT), and big data analytics) [9,24]. The primary concern of functioning Industry 4.0 is to achieve greater efficiency and accuracy, making these Industry 4.0 technologies potentially vital productivity-enhancing tools. They help cope with data-rich systems that are fulfilled with heterogeneous attributes. Likewise, the growing prevalence of digital technologies has propelled the research efforts on Industry 4.0 from vision to reality. Hence, there is a large body of extant literature that has elaborated on theoretical and empirical studies varied disciplinary backgrounds within the scope of Industry 4.0 [7,9]. However, social and environmental sustainability receive slightly less importance in the transformative age of Industry 4.0 [7]. Since enterprise objectives increasingly include advanced sustainable developments with focuses on human centricity and societal goals, the Fifth Industrial Revolution (Industry 5.0) emerged as a new phenomenon [23]. Although previous scholars point out Industry 4.0 can contribute to sustainable manufacturing at the operational level, it often overlooks the priority of well-being. In contrast, Industry 5.0 emphasizes being sufficiently participatory in building a socially intelligent and responsible environment [137,152].

As revealed in a recent paper titled “Industry 5.0 : Prospect and Retrospect” by [23], the wake of Industry 5.0 is driven by “Industry 4.0”, “Society 5.0”, and “Operator 5.0”. Society 5.0, also known as “Super Smart Society”, is a concept proposed by the Japanese government in 2016 to update the socio-technical relationship in the manufacturing-centered Industry 4.0 and build a human-centric society that benefits humankind [9]. Society 5.0 aims to strike the balance between the increasing pace of productivity requirements and the enhancement of individuality [153]. The theoretical background of Industry 5.0 is characterized by a collective emphasis on society-centric and human-centric approaches. Industry 5.0 can be seen as a natural response to the technology-driven Industry 4.0 and an increased awareness of the importance of human-technology companionship and human-automation symbiosis [23]. The arrival of Industry 5.0 reframes the role of humans in various industrial fields and complements the ongoing Industry 4.0 [7,12]. However, the current circumstance is that the acceptance and implementation of Industry 4.0 remains unfulfilled, while Industry 5.0 is a proactive but premature strategy with vague conceptions [104]. Consequently, the evolutionary conceptions of Industry 5.0 are the main content of current research publications.

4.2.3 Industrial XR

From a technical perspective, XR is a tool capable of producing artificial virtuality, allowing for the presentation of interactive replicas in the form of stereoscopic animations. From a scientific-research standpoint, XR serves as an umbrella term embracing AR and VR technologies, which are utilized to establish essential human-virtuality-reality companions. XR is a rapidly expanding field that involves interdisciplinary collaborations and theoretical advancements [143]. AR, launched into mobile applications frequently, overlays virtual images to reinforce the physical environment [143]. The experiential management of AR facilitates the delivery of transient, intuitive, and interactive responses to the surrounding physical materials. VR provides fully virtual objects with a high level of representational fidelity within an immersive universe [14]. Creating and visualizing AR or VR content requires the convergence of wearable or hand-held devices (e.g., head-mounted displays or tablets), controllers, three dimensional (3D) development tools, and so forth. It is worth noting that XR is not a new round of technology; it has been extensively investigated in diversified application areas [154]. For instance, both AR and VR have demonstrated their effectiveness in domains such as shopping [86, 155], education [156, 157], construction [65, 158, 159], and manufacturing [15, 143]. With advancements in lightweight devices, high-resolution visualization, affordance actualization, the maturity of XR technology improves its adaptability across multiple sectors. On this basis, there is sufficient room to explore acceptance antecedents, challenges, and barriers for XR in various sectors for further investigation and discussion [143]. Since the conceptual boundary of MR is relatively indeterminate and the similarity between AR and MR has been established, this study does not specifically cover MR. The scope of research on XR focuses on its constituent technologies, AR and VR.

In recent years, the promotion of AR and VR has been widespread with the emergence of Industry 4.0, leading to the recognition of “Industrial XR” [116, 143]. The integration of industrial XR has the potential to drive digital transformation for enhanced competence and competitiveness [104, 160]. On the whole, industrial XR has primarily been adopted as a visualizing and monitoring assistant in service-oriented applications [147]. In addition to providing special visual effects and allowing for the synchronization of physical and virtual scenes, XR is also extensively used for operator training and remote collaboration, enabling interactions between local operators and remote experts [116]. For the design of decision-support systems, XR can aid in simplifying and visualizing the information representation of production and processes by generating virtual replicas, thereby intensifying overall operational quality. Real-time simulation, powered by immersive computing techniques of XR, can facilitate EoL product representation by playing the role of an independent observation during decision-

making processes [15]. Additionally, the interconnectivity with other technologies, such as DT and AI, makes XR a versatile and compatible decision tool. The coordination and co-operation with other potential enabling technologies can improve the self-decision-making level of the disassembly system. To tackle EoL management in uncertain environments and market volatility, XR can be considered as potential analytics-related technologies. Hence, XR has the potential to contribute to cost-effective disassembly planning within the realm of advanced manufacturing technology.

Incorporating XR into operational and system workflows equally benefits Industry 5.0. XR deserves more attention for the successful transitioning from Industry 4.0 to Industry 5.0 [142]. In general, high-level XR products and services are expected to create substantial positive effects on the user experience. In the case of industrial XR applications and devices, the initiatives and deliveries should concentrate more on human factors to reduce physical stress and ergonomic tensions [161]. During the development phase, it is crucial to highlight the technological acceptance that involves engaging with human well-being and safety. Furthermore, the recent development of multiplayer XR applications enables improved decision-making environments, allowing stakeholders to engage without location restrictions. In line with the social communication aspects of VR literature [154], immersive socializing is also a part of virtual networking via human-like avatars [162, 163]. Consistent with the principles of Industry 5.0, achieving superior industrial XR requires more journeys to improve technological capabilities while considering laws, regulations, and ethics. XR is also required to relate the vision of Industry 5.0 in order to make concerted efforts on the benefit of humankind. Industry 5.0-driven XR can serve as a timely extension of practical fulfillment to enlighten the human-centered industrial revolution.

4.2.4 Lean disassembly

In the face of uncertain operational challenges, lean management has sustained a favorable impact by improving operational performances while simultaneously reducing various forms of waste (e.g., unnecessary lead-times, defects, motion, inventory, and costs) [2]. It is important to emphasize that earlier research has shown that the successful implementation of lean can also produce tangible benefits for sustainability beyond just profits and customization intentions [164]. By focusing on waste reduction and efficiency improvement, both intra- and inter-organizational sustainable performances can be improved. Lean tools also have noticeable and positive impacts with varying degrees of diminishing negative environmental effects [145]. For instance, VSM can be used to reduce energy and material consumption and workshop space utilization. Since lean improvements are related to environmental sus-

tainability, some papers [13, 90, 165, 166] indicate that lean disassembly can be a systematic approach at the end of life.

With the commitment of lean management, lean disassembly encourages organized managerial manners with strong self-adaptiveness capacities. More concretely, by applying VSM to eliminate and prevent wasteful operations at every stage of the disassembly process planning, from initiation to completion, predictability can be increased by minimizing variations. Meanwhile, operational performance and customer satisfaction can be improved through kaizen thinking at a competitive cost within limited resources. The practical implementation of just-in-time systems can provide quick responses to varying demands. Hence, lean disassembly can be applied successfully to differentiate between waste and value in dynamic environments. Moreover, as mentioned in Section 1, one advantageous point of lean disassembly is that it can accept the integration of emergent technologies to enhance operational capabilities and long-term profitability [56]. Similarly, [96] examined the applicability and usefulness of “Lean Manual Assembly 4.0” by combining lean principles with the implementation of digital technologies. They explored the potential for increasing added value and demonstrated that lean serves as the “starting point” for smart environments. They specially mentioned the application of XR for training novices in lean assembly and providing timely feedback on operator performance. Lean disassembly management and digital lean transformation also involve collaboration, particularly in the context of XR integration. In our previous publication [13], we investigated the implications of XR and lean integration in disassembly planning, and we proposed XR–lean smart disassembly planning as a result of our comprehensive literature review.

Crucially, similar to Industry 5.0, lean can place a predominant focus on the role of humans in manufacturing systems. In addition to the above-said environmental sustainability, lean is naturally interconnected with social sustainability and lean disassembly similarly calls for considering humans as a fundamental factor. Insights from related literature [16, 167] highlight the inherent relevance of ergonomics and lean transformation. Lean can prioritize the quality and correctness of shop floor and workstation layout while ensuring safe working conditions. For instance, a lean tool, 7S, elaborates continuous improvement of the workplace to keep it safe and sustainable [16]. Likewise, effective ergonomics strategies can contribute to the continuous improvement of productivity by reducing labor injuries and associated losses. As for manual disassembly activities associated with highly repetitive motions, stressful postures, or heavy workloads, the support to humanity can positively impact the implementation of lean processes [16]. In this study, the devised lean disassembly focuses on improving existing disassembly processes by coping with identification and elimination of non-valuable human activities. A safe, inclusive, and lean disassembly environment can be established by the

guideline of Industry 5.0 on a purposive basis.

Section 2 provides an overview understanding of Industry 5.0, XR, and lean, particularly in relation to EoL disassembly research. The foundational theoretical concepts of these terms or areas are outlined above. An overall description of their developmental relationship at this stage is illustrated in the Venn diagram (see Figure 4.1). Combined with research profiling in section 1, the summary of theoretical foundations to comprehend the possible association is presented in Figure 4.2.

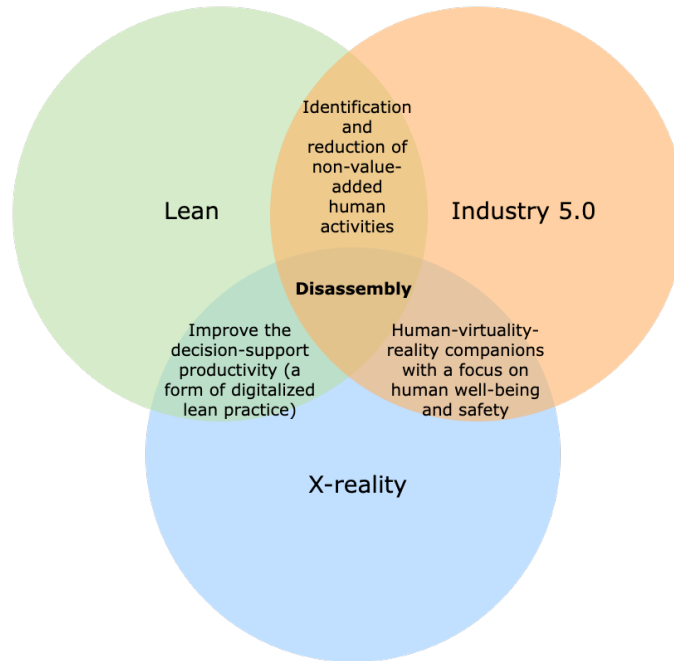


FIGURE 4.1 An overall description of the developmental relationship between lean, Industry 5.0, and XR

4.3 Research methods

The present study aims to explore emerging research topics and follows the systematic literature review process recommended by three recent review papers : Frederico (2021), Naeemah and Wong (2022), and Sanguineti et al. (2023). The systematic literature review is broken into three steps : planning, conducting, and reporting as depicted in Figure 4.3. In the planning phase, research objectives, questions, and the search strategy are defined, along with the search query, databases (i.e., scientific citation databases to retrieve peer-reviewed articles), and criteria. During the conducting phase, the literature selection strategy is unfolded, including the application of inclusion and exclusion criteria to facilitate the practical screening

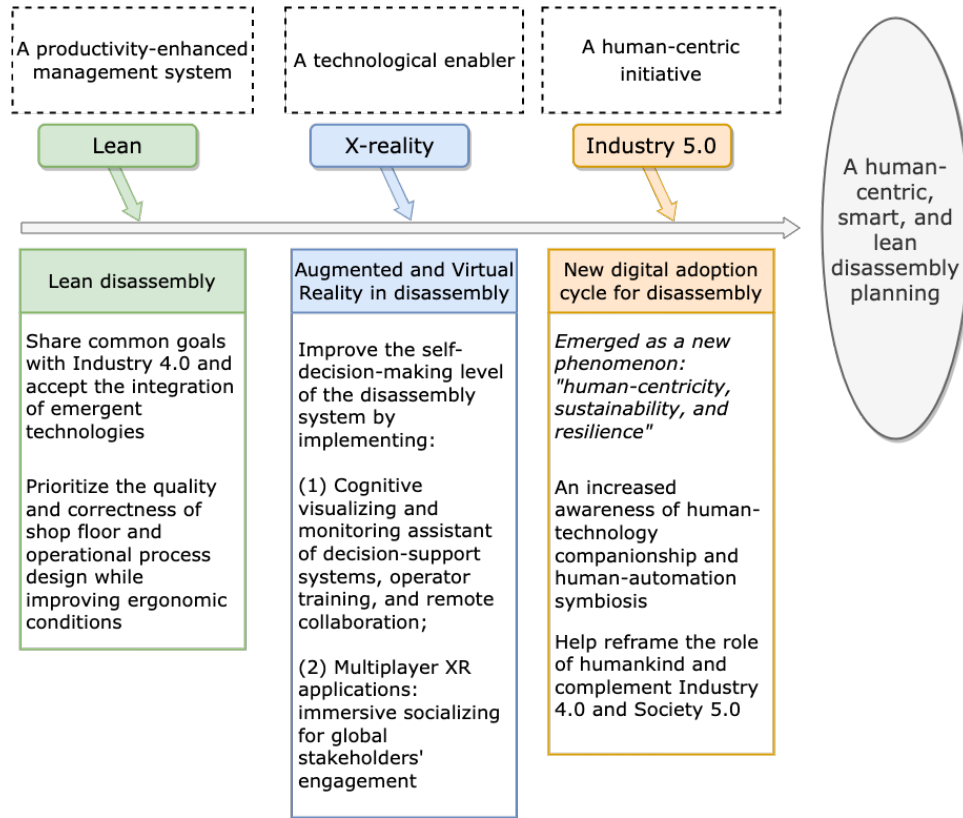


FIGURE 4.2 The summary of theoretical foundations

process. The final sample is extracted manually, considering the scope of the study. In the final reporting phase, a detailed descriptive and thematic analysis is conducted on the selected articles, and a bibliometric visualization analysis is employed to examine the topic network mapping.

4.3.1 Phase 1 : planning the review

Three comprehensive web-based databases, Elsevier Science Direct, Taylor & Francis, and Springer Link, were selected during the planning phase. It became apparent that the direct search combination of “disassembly”, “Industry 5.0”, “Lean”, and “X-reality” could not effectively address the issues in this study. For example, the initial search query *"disassembly" AND "Industry 5.0" AND "lean" AND ("augmented reality" OR "virtual reality")* in Elsevier Science Direct, without refining and filtering, yielded only 2 research papers in June 2023. Therefore, it was necessary to develop a tailored search strategy that considers the distinct characteristics of all keywords in order to reformulate the search query. Moreover, the delivery of keyword form should have a sharper focus on named research questions of this study.

Phase 1- planning the review
Identifying research aims and questions
Defining the search strategy, databases, string, and criteria
Phase 2- conducting the review
Searching, filtering, and refining the relevant studies in search engines
Extracting data for the final sample
Phase 3- reporting the review
Documenting descriptive analysis and reporting results visualization
Obtaining the review results for the detailed thematic analysis

FIGURE 4.3 Overview of research method

In the present multidisciplinary review, the keyword form should be broadly yet accurately descriptive. The search terms have been classified into four categories and are presented in Table 4.1. In line with the required efforts in Industry 5.0 scenarios in Section 4.1 and 4.2, both “human” and “society” were considered in the string of keywords. Even though the triple pillars of Industry 5.0 are suggested to be human-centricity, resilience, and sustainability, it is vital to elaborate on societal transformation and human-in-the-loop employment to highlight the generalization of literature. Apart from the core keyword “disassembly”, “circular” and “sustainable” should be included in the search because they can reflect the attitudes of major manufacturing activities implemented at the end of life. XR technologies and lean are also important components in the search query. In agreement with the research scope identified in Section 4.2.2, the focus of XR technologies specifically spans “virtual reality” and “augmented reality”. Therefore, the combination of keywords used with both the “OR” and “AND” Boolean connectors, (*"disassembly" OR "remanufacturing" OR "sustainable manufacturing"*) AND (*"Industry 5.0" OR "human" OR "society"*) AND *"lean"* AND (*"augmented reality" OR "virtual reality"*), was defined as the primary search query.

TABLEAU 4.1 The search terms

Category	Keywords
Industry 5.0	“Industry 5.0” OR “human” OR “society”
Manufacturing type (disassembly)	“Disassembly” OR “remanufacturing” OR “sustainable manufacturing”
Lean	“Lean”
X-reality	“Augmented reality” OR “virtual reality”

Correspondingly, regarding the search criteria, some restrictions related to the time frame, publication type, and research subject were imposed in the final planning step. The litera-

ture research was conducted in June 2023. Because academic discussions on Industry 5.0 commenced in 2015, this review decided to cover the period starting from 2015. To obtain clear insights from more high-quality research works, only journal articles and conference papers were considered. In order to ensure all relevant publications were included, subject areas such as Engineering, Business, Computer Science, Decision Sciences, and Social Sciences were covered. However, it is important to note that this review does not focus on all possible anticipated applications (e.g., healthcare and linear manufacturing).

4.3.2 Phase 2 and 3 : conducting and reporting the review

As depicted in Figure 4.4, conducting the review involves the actions of screening and selecting the required content based on the search criteria mentioned above. The first step involves using an automated application of the search criteria in Elsevier Science Direct, Taylor & Francis, and Springer Link. A total of 352 studies were obtained from the search engines. The initial sample was collected from three different databases, and a custom Python script, along with Mendeley and JabRef software, was used independently to gather and organize the data in CSV (Comma-Separated Values) format. Subsequently, after screening the initial sample based on titles, 253 articles were retained for documentation. To provide a comprehensive overview, this study utilized Microsoft Power BI and VOSviewer for visualization and descriptive analysis, as presented below. Figure 4 presents the proportions and numbers of articles among all retrieved journals. It can be observed that the largest number of publications (25 papers) were published in the Journal of Cleaner Production (Elsevier), followed by the Procedia Manufacturing (Elsevier) with 20 papers. The other significant journal names included Procedia CIRP (Elsevier), IFAC-PaperOnLine (Elsevier), International Journal of Production Research (Taylor & Francis), and International Journal of Computer Integrated Manufacturing (Taylor & Francis).

Based on the inclusion criteria, Figure 4.5 displays the evaluation of publications during the period since 2015. Considering that the year 2023 has not finished yet, it can be observed that the trend of developing XR-related disassembly planning under Industry 5.0 is still increasing.

Moreover, in this phase, VOSviewer was applied to generate a keyword networking map, providing an overview of recent academic interests (see Figure 4.6). VOSviewer software facilitates bibliometric visualization for topic mapping analysis [104]. Despite the increasing popularity of Industry 5.0, Figure 6 shows a high dependence on Industry 4.0, along with strong interconnections between them. Other keywords with significant co-occurrences (represented by colored nodes) include sustainability, circular economy, smart manufacturing,

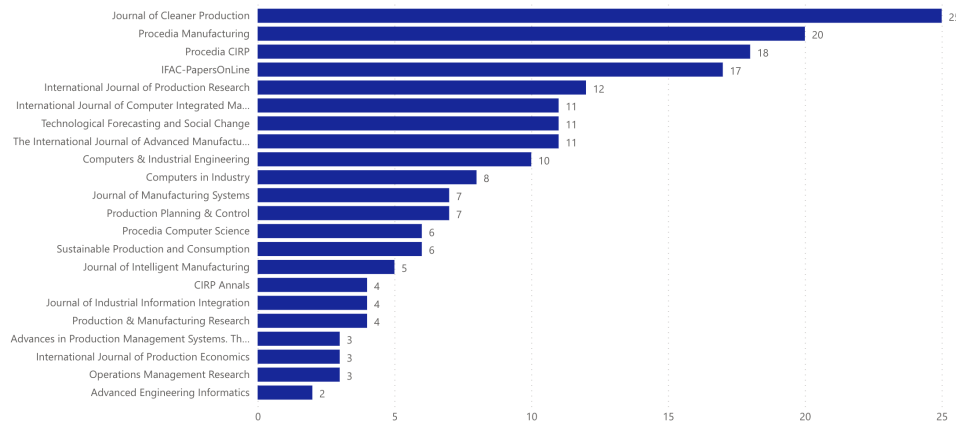


FIGURE 4.4 The proportions and numbers of articles per journal

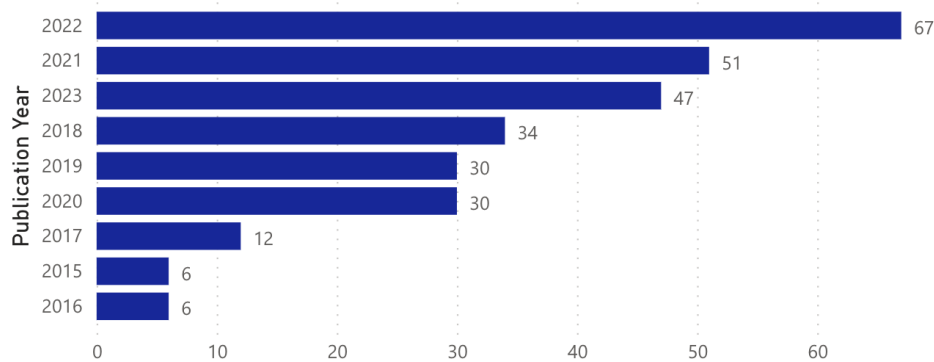


FIGURE 4.5 Quantity of the relevant publications since 2015

sustainable manufacturing, and so forth. Furthermore, previous scholars have also discussed the triple bottom line perspective, which encompasses the environmental, social, and economic dimensions of sustainable development [12].

To retrieve the most relevant publications, unrelated results were discarded by manually examining the titles and abstracts. As a result, a list of 92 papers was retained in the final sample and thoroughly read for further detailed content analysis in the next section.

4.4 Review and content analysis

To explore the current state of knowledge and answer all research questions emphatically, this section discusses the review results on the existing intersections between Industry 5.0, XR, and lean for disassembly studies. Given these interconnected research objects, the content analysis in this section is divided into three parts : (1) the fundamental integration of Indus-

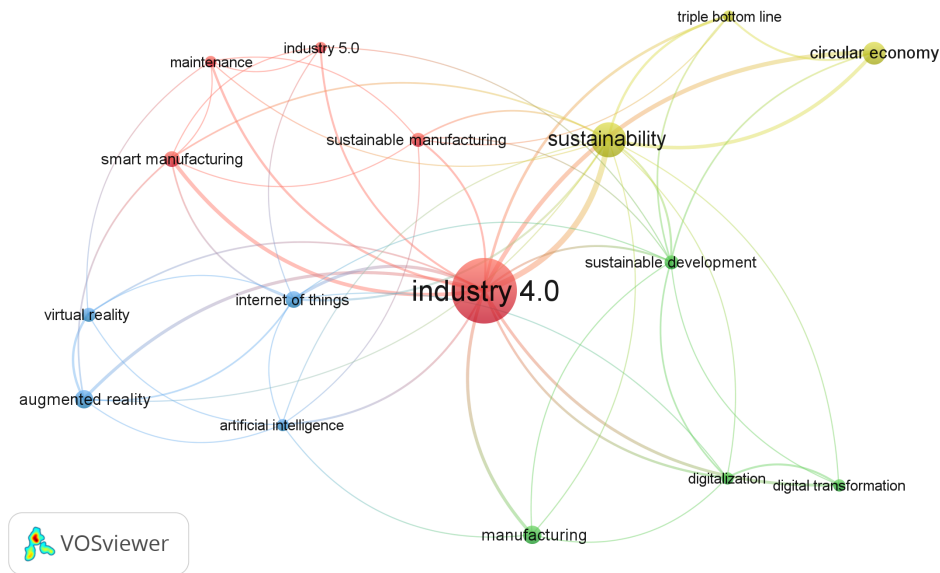


FIGURE 4.6 The co-occurring keyword links of the relevant publications

try 5.0 and lean in sustainable manufacturing; (2) XR-focused applications in disassembly planning under Industry 5.0; and (3) the derivable conceptual framework based on the joint implementation of these three elements in disassembly systems. The arrangement of each subsection corresponds to the research questions in sequence.

4.4.1 The constructs for Industry 5.0 and lean in sustainable manufacturing

Most of the shortlisted articles focus on exploring the architecture and implementation approaches of Industry 5.0 while also theorizing its research development. The association of Industry 5.0 and lean in the context of sustainable manufacturing is the main focus of this subsection.

To accurately understand the benefits of Industry 5.0 in implementing lean management, it is also essential to have a clear understanding of Society 5.0, as discussed in the research profiling in Section 2. [168], for instance, compared and correlated Society 5.0 and Industry 5.0 based on their respective concepts. They emphasized that the goal of Society 5.0 is to ensure a “human-centered, super-smart, and lean society” [168]. The value co-creation of Society 5.0 contributes to the continuous improvement of organizational efficiency while considering customer preferences. Additionally, the non-value-added elements to be eliminated can include suppressive influences on individuality (e.g., gender and race) and as well as contribute to low self-esteem. [169] explained the implications of Industry 5.0 in sustainable manufac-

turing by operationalizing the concept, proposing an architectural design, and identifying 12 Industry 5.0 sustainability functions. Based on these three-fold conceptual findings, they developed a strategic roadmap to establish contextual relationships for each pair of Industry 5.0 sustainable manufacturing functions. All functions were identified and summarized with the aim of improving industrial productivity and socio-environmental values. Examples of these functions included, but were not limited to, “work environment smartification”, “manufacturing strategic adaptability”, and “manufacturing circularity” [169]. Crucially, one of the functions emphasized was “manufacturing responsiveness”, which was explicitly underlined as a lean-driven approach. The aim of setting “manufacturing responsiveness” was to apply lean approaches to guide the structural engagement of manufacturers in achieving operational excellence. [152] derived a technological-organizational framework of Industry 5.0 spanning society level, network level, and plant level. “Lean resilience” was highlighted at the network level of the framework, considering the development of costs and investments in resilience. The author suggested “lean resilience” as a solution to cope with high costs and resource consumption caused by some operational redundancies in emergency cases. [23] identified humans as the driver of Industry 5.0 and pointed out that preventing worker errors was one way of improving human performance. From our view, since a lean tool, poka-yoke, aims at prohibiting working mistakes, the human-centric vision of Industry 5.0 can be integrated into it.

In addition to the literature focused solely on Industry 5.0, [170] conducted a systematic review and framework analysis to establish a comprehensive association of the four paradigms (lean, green, smart, and resilient) in manufacturing. Three prominent characteristics (i.e., human-centricity, sustainability, and resiliency) of Industry 5.0 are significantly overlaid with these integrated paradigms. However, they also explored contrasts between the four paradigms and noted that lean and resilience can sometimes be contradictory. While resilience in manufacturing can be achieved through redundancy, it may lead to increased costs due to investments. On the other hand, lean aims to eliminate waste and increase profitability. In this regard, [170] proposed the importance of reaching optimal trade-offs and presented the integration of digital technologies as a timely solution. This aligns with the existing literature on the collaboration and complementation of digital technologies and lean. Table 4.2 provides a summary of the references related to Industry 5.0 and lean in sustainable manufacturing.

TABLEAU 4.2 Recent literature specific to Industry 5.0 and lean in sustainable manufacturing

Authors	Objectives	Methods	Highlights
[168]	To present conceptual propositions between Industry 5.0 and Society 5.0 from the aspects of comparison, the shared fundamentals, and complementation	Literature review and conceptual analysis	Lean is an essential goal of Society 5.0, and Society 5.0 and Industry 5.0 share the same foundation and are closely intertwined
[169]	To understand how Industry 5.0 agenda can promote inclusive and sustainable manufacturing	A content-centric literature review and expert opinion analysis to arrive at a strategic roadmap (reference document)	Offered an operational definition and identified 12 sustainability functions of Industry 5.0 within the sustainable manufacturing context, Additionally, introduced the Industry 5.0 reference architecture and developed a strategic roadmap for Industry 5.0-driven sustainable manufacturing
[152]	To provide a definition of Industry 5.0 by developing an operations and supply chain management framework for Industry 5.0	Literature review and framework analysis	Laid out a detailed Industry 5.0 agenda and introduced “lean resilience” as a solution to cope with high costs and resource consumption caused by some operational redundancies in emergency cases
[23]	To review the evolution of Industry 5.0, this study aims to explain its definition, features, and the diversified essence from different perspectives	Literature review and framework analysis	Developed a value-driven Industry 5.0 model built by a tri-dimensional architecture (technical dimension, reality dimension, and application dimension) to specify the key enabling technologies. Identified humans as the driver of Industry 5.0.
[170]	To investigate the present trends and future research possibilities of four combinatorial paradigms of smart, green, resilient, and lean in the manufacturing domain	Literature review and framework analysis	Developed an integrated model for the association of four paradigms, summarized its theoretical elements and critical success factors, and identified 8 possible directions in the context of manufacturing

4.4.2 XR-integrated disassembly planning in the era of Industry 5.0

Despite not being included in the search terms, Figure 4.6 reveals that Industry 4.0, digital transformation, and digitalization are unavoidable synergies found in the reviewed papers. There is a significant body of literature available on the topic of Industry 4.0, and it has influenced Industry 5.0. Based on the contextualization provided in Section 4.2, the connotation of Industry 5.0 is driven by the utilization of technologies from Industry 4.0 [20]. This subsection aims to provide a multifaceted understanding of XR as a crucial technological constituent to ensure the viability of Industry 5.0. In addition to channeling the use of XR (AR and VR) in human-centric and reconfigurable disassembly planning systems, this subsection will focus on the pathway through which Industry 5.0 can further facilitate the transition from vision to realization.

Before XR technologies can be envisioned as key enabling technologies of Industry 5.0, XR has already been recognized as an enabler of human-centric digital products and services. Computer-aided manufacturing and supply chain management are primary research fields as they require the integration of various digital technologies to enhance value creation across the entire chain. In the identified relevant papers, above-mentioned [23] emphasized the simulation capabilities of XR in Industry 5.0 and highlighted application areas such as virtual prototyping of production processes and personalized education. [171] examined the technological components of Industry 5.0 in their content-based review and explained the benefits of XR. However, they also suggested that to overcome technical limitations, such as motion tracking and internet connectivity issues, other data-driven and cognitive computing technologies like DT, AI, IoT, and big data analytics should offer advanced data processing and information sharing capabilities. This observation aligns with the relatively high co-occurrence of AI and IoT in the extracted relevant publications shown in Figure 4.6.

To bring human-centricity from vision to reality in disassembly systems, XR can provide a virtual environment for implementing human-in-the-loop decision analytics. [22] designed an integrated framework for EoL disassembly planning to improve human ergonomics. By incorporating human factors into the entire framework, step tracking and ergonomic monitoring can be implemented using a sensor network and a multi-objective search and optimization algorithm. Due to the integration of a series of sensors, several technologies (AR, VR, and IoT) were considered to apply in their study towards advanced human computer interaction. [172] conducted a survey on human-centered assembly and disassembly systems, highlighting the use of motion capture technology for optimal decision-making considering ergonomic aspects and human productivity measurement. They identified VR as a suitable technology for recording and analyzing human movements. In terms of quality management, XR can support

real-time information description during disassembly preparations and operations. [80] developed a VR simulation environment to simulate multiple process scenarios for cabin and cargo assembly tasks. By capturing motion data of avatars in VR environments, they analyzed productivity and ergonomics of the assembly process. Similarly, in the context of disassembly processes, planning and evaluation can be improved through a digitalized parallel universe created by VR.

Furthermore, XR technologies play a role in mutual cognitive support and visual assistance, thereby reducing the risks associated with dangerous and challenging labor-intensive operations. Both AR and VR can digitally recreate customer-tailored content to train engineers and workforces. [173] proposed the conceptual development of “Resilient Operator 5.0,” aiming to achieve “cognitive resilience” and build resilient manufacturing systems. They suggested using AR to assist the workforce in maintaining mental abilities under stress and avoiding human errors. Table 4.3 provides a summary of the shortlisted articles specific to XR-assisted disassembly planning systems under Industry 5.0.

TABLEAU 4.3 Recent literature specific to Industry 5.0 and XR in human-centric disassembly systems

Authors	Objectives	Methods	Highlights
[22]	To propose an integrated framework for EoL disassembly planning that considers appropriate human factors and ergonomic conditions to improve human ergonomics	Literature review, framework analysis, and case study	Potential integration of AR and VR in the framework, considering the criteria of human factors and ergonomic conditions
[171]	To identify all existing enabling technologies of Industry 5.0 and develop an architectural design	A content-centric literature review	To advance X-reality technologies toward Industry 5.0 applications, it is important to consider the collaboration with other virtual-physical or data-processing technologies
[172]	To present and explain existing ergonomic measurement and human productivity measurement approach of human-centric disassembly and assembly systems from the literature	Literature review	The combined use of Virtual Reality and motion capture technology can be employed in the analysis of productivity and ergonomics in human-centric disassembly systems
[80]	To develop and present a Virtual Reality product for simulating cabin and cargo assembly tasks and evaluating multiple new assembly scenarios	Design science and empirical study	Virtual Reality can be utilized to analyze the effectiveness of (dis)assembly line processes by modeling them and using operator-avatar interactions
[173]	To propose the conceptual development of “Resilient Operator 5.0”	Literature review	Augmented Reality can assist the workforce in maintaining mental abilities under stress and avoiding human errors in the context of resilient manufacturing systems and Industry 5.0

4.4.3 HSL integrated model : the combinatorial possibility of Industry 5.0, XR, and lean in disassembly systems

Based on the concept interpretation and industrial cases apprehended from past literature, it can be stated that Industry 5.0, XR, and lean were investigated in isolated ways, treating one or two as a unit. The synergies jointly created by Industry 5.0, XR, and lean are conveyed to their descriptive essences : human-centric, smart, and lean (HSL), in this preliminary exploration stage (shown in Figure 4.7). In accordance with RQ3, the intention of this study was to elaborate on the responsibilities and collaboration between the paradigms of HSL for a clearer understanding of the triangulation.

While responding to competitive pressures, the HSL framework should satisfy multiple constraints among humans, operations, computers, and machines simultaneously. As presented in Fi-

Figure 4.7, the HSL framework embraces six theoretical components (i.e., human well-being, human safety, circular improvement, operational excellence, digitalization, and customization) that are grouped by human-centric, smart, and lean independently. Each of the theoretical components is also identified in this subsection. To help explain the HSL structure and link it with XR and lean, we present another illustration (see Figure 4.8) below. Even though it is known from literature that the potentialities associated with the integration of XR and lean are enormous, at this moment, it is still unclear which roles they can play to achieve the associated benefits. Figure 4.8 describes the techno-functional details that XR and lean can contribute to the decision-making contexts of EoL disassembly research under Industry 5.0. Three groups coexist harmoniously, and each group entails the responsibilities and collaboration of lean thinking and VR/AR solution.

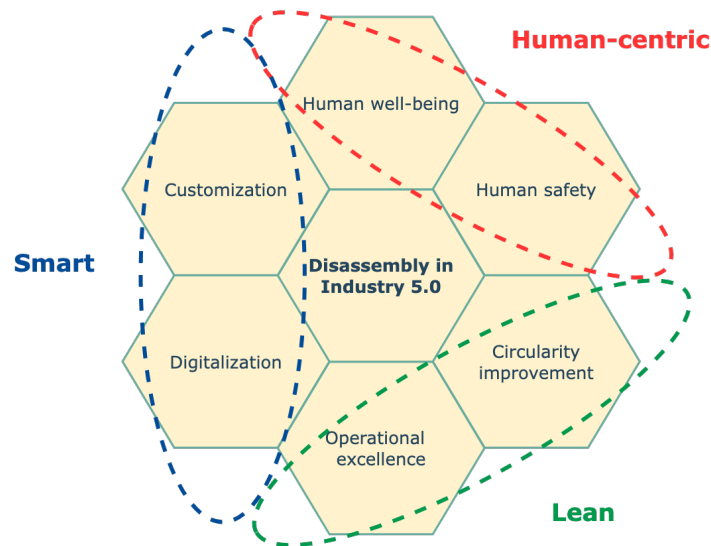


FIGURE 4.7 A general architecture of human-centric, smart, and lean (HSL) framework

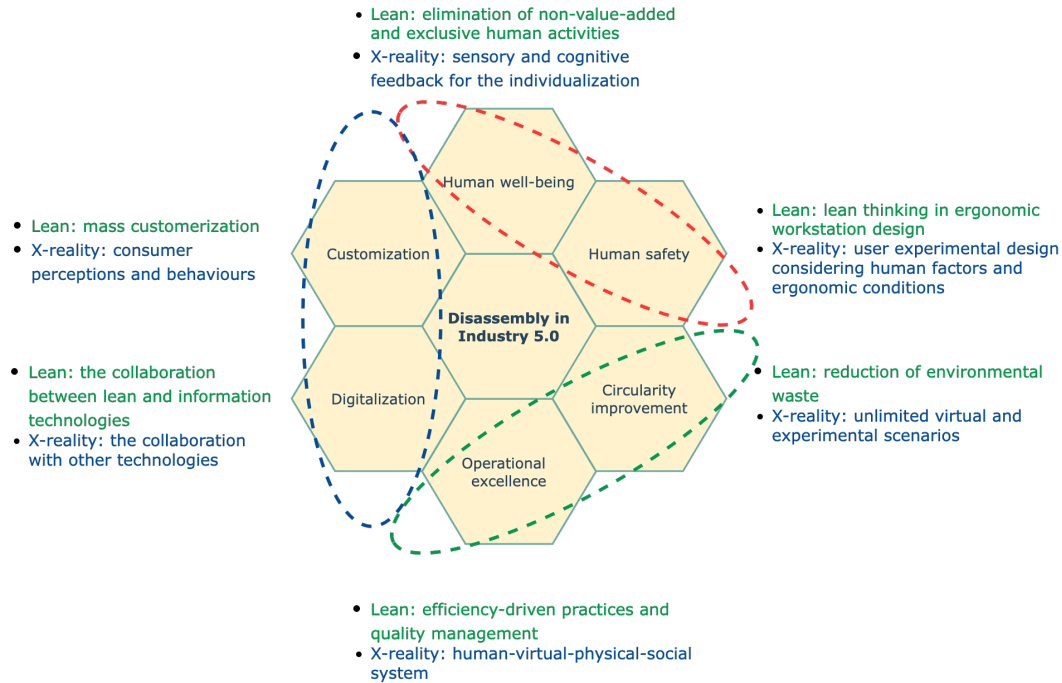


FIGURE 4.8 The joint implementation of X-reality and lean in the human-centric, smart, and lean (HSL) framework

4.4.3.1 Human-centric group

Since the inception of Industry 5.0 stems from the awareness of the harmonious symbiosis between humans and intelligent systems, human-centricity should be an important intrinsic composition of the HSL framework [23]. This group includes two essential theoretical elements, human well-being and human safety. The "H" of HSL means it can place significant emphasis on the employee productivity, well-being, fatigue, physical health, mental health, and safety. Consequently, HSL implies the main responsibility of an Industry 5.0-driven framework to prioritize a human-centric and society-centric working environment.

Lean and "H" In response to significant social changes, the identification and elimination of unnecessary human activities and non-utilized talent have become integral aspects of lean thinking from the perspective of social sustainability [88]. Furthermore, it is important to reiterate that lean has a strong connection with ergonomics by prioritizing operator safety [145]. Apart from the built-in functionality of 7S (see Section 4.2.4), VSM can be exemplified as integrated into HSL. For instance, ErgoVSM, a VSM tool developed by [174], integrated an ergonomics add-in module into an existing VSM system, considering phy-

sical exposure in the analyzed manufacturing processes. They subsequently validated it in a Swedish manufacturing company. In addition to decreasing unnecessary physical burden on human operators, the improvement of team spirit and employee engagement can receive positive support from lean. Some scholars ([145, 167]) indicated that the transformational directions of lean might be more about culture change. The culture of lean can promote more human-centric cooperative work, considering the inner qualities (e.g., personality and sensibilities) of human beings when combined with ergonomics applications. HSL can exert its strength in promoting human well-being by transforming the organizational culture into a leaner culture.

XR and "H" XR is a promising technology to serve the "H" group. Introducing human-centric thinking into XR applications is not new, and user-friendly XR experiential design is an increasingly mature research area. For the workstation where the disassembly tasks are executed, continuous improvements in safety and flexibility of workstation design are required. VR is a well-adapted means to design and assess physical workplaces because it allows the creation of an immersive virtual environment where users can manipulate and interact with virtual representations in real-time using their natural senses and abilities [80, 81]. Hence, VR can largely reduce the extra workload of learning compared to other complex computer-aided systems. Specifically, coupling the application of VR and motion capture systems can reduce the need for physical mock-ups associated with the consumption of time and resources. Therefore, VR can accelerate and simplify the workplace design procedures while considering the right ergonomic interventions simultaneously [81]. It is noteworthy that [175] developed a system that allowed operators to be equipped with VR devices, motion capture systems, and a heart rate monitoring system to evaluate the level of fatigue. For the improvement of human well-being, the feedback and measurement of humans' emotional response and cognitive abilities can be highly integrated into "H" for individualization with the application of XR. Following this, the personalized user interface adaptation can be implemented in XR. To reduce human labor intensity within the HSL framework, XR is a practical way to seamlessly integrate into the "H" group.

4.4.3.2 Lean group

To deliver a value-producing HSL framework, lean underlies the managerial pillar of HSL. Sustaining remanufacturers' competitiveness, the lean group is a decisive factor. Even though humans take the leading role in HSL, the lack of management involvement can create barriers to the improvements of operational performance and productivity in disassembly planning.

Moreover, Lean is irreplaceable, and its survival indicates that its managerial philosophy continues to serve and impact manufacturing and production systems. The theoretical elements of the lean group are summarized as "circular improvement" and "operational excellence". To serve "circular improvement," both AR and VR can provide virtual prototypes, allowing users to experiment, assess, and redesign the guidelines of disassembly operations and workstations. Moreover, VR can simulate and deliver an unlimited immersive workspace for users to navigate [157]. To support "operational excellence," XR can provide a decision-making environment that is closely involved in the virtual-physical interaction loop to alleviate the challenges of uncertainties. Due to the integration of XR and the perspective of Industry 5.0, HSL can be enlightened by some recent heterogeneous system integration concepts, such as human-cyber-physical systems and cyber-physical-social systems [23, 168]. Through content analysis and a conceptual framework, it can be concluded that the blending of human-virtual-physical-social capabilities is revealed in the HSL framework. While proposing the "L" group of the HSL framework, the factors of balancing economic advancement with societal goals and centering human involvement are still imperative. Consequently, this study tends to apply the human-virtual-physical-social system as the core heterogeneous system for the HSL framework.

4.4.3.3 Smart group

Since Industry 4.0 is indeed one of the drivers of Industry 5.0, their consensus includes digitalization. Moreover, technologies booming in the era of Industry 5.0 can embrace all Industry 4.0 technologies or a handful of digital technologies. Therefore, HSL should concentrate on the adoptions of assistive and supportive digital technologies in the design and development of operational systems. Regarding the endeavors of XR and lean in the setting of digitalization, collaboration is at the core. The hybrid lean-digitized (re)manufacturing systems can continue their competitiveness since the Industry 4.0 era [93]. XR is open to cooperating with other intelligent technologies, such as DT, IoT, and AI. Hence, the extended functions of HSL can include the technology acceptance measurement of the future technological association. XR in the HSL framework will not be isolated in development. Although the roles of humans include but are not limited to operators, decision-makers, observers, and customers, finding ways to positively affect consumers' attitudes and behavioral intentions is particularly vital for proposing and implementing HSL. Some recent papers provide reference value for the discussions of the concept and evolution of Industry 5.0; however, there is a scarcity of studies that examined the consideration of customization and the impact of customer value. Likewise, the integration of XR and lean also enables the role of customization emphatically. To guide the transition towards Industry 5.0, prevailing over Industry 4.0, customization cannot

be neglected. The built-in characteristic of lean thinking or culture focuses on customer value. The applications of both AR and VR are wide-ranging, spanning shopping, retail, online gaming, education, and tourism sectors over the past two decades, for example, virtual showrooms [86, 155]. They are promising enablers to change communications and consumption experiences in participatory research by perceived user experience measurement. To meet customer expectations, the XR applications can be designed and developed dynamically and actively in various business contexts. Following these two components, digitalization and customization, the last essence of HSL is derived as the smart group in reverse. The HSL framework is expected to transition from a smart system to a smarter society-technology system.

4.5 Conclusion

In this context, the joint implementation of Industry 5.0, XR, and lean is emerging as an effective solution and a triangulation. The general purpose of establishing this association is to foster creativity and critical thinking for future disassembly research. To accurately grasp the research background and literature, we examined the conceptualization of EoL disassembly planning, Industry 5.0, industrial XR, and lean disassembly first based on research profiling from our preliminary investigation, as well as related concepts, Industry 4.0, and Society 5.0. This stage provides the necessary input for the bibliometric analysis, and we conducted a systematic literature review by planning, conducting, and reporting descriptive and content analysis. In accordance with research aims and questions, the content analysis has three parts : (1) the fundamental integration of Industry 5.0 and lean, (2) XR-assisted disassembly planning under the impact of Industry 5.0, and (3) the integrated structure of the association. In the third part of content analysis, to discern and assess the proposed triangulation (Industry 5.0, XR, and lean) in-depth, this study analyzes the HSL framework by studying the responsibilities and collaboration of HSL components (human-centric, smart, and lean) with interactions between XR and lean. Consistent with the core value of Industry 5.0, HSL allows "humans" to be integrated into the entire framework. Most disassembly operations are still implemented manually, where human intervention is still heavily required. The human-centricity of Industry 5.0 is a timely and directional advancement for the development of disassembly systems. With the aim of prevailing over Industry 4.0-based disassembly systems, sufficient planning guided by the HSL structure plays a critical role in guiding XR and lean to accommodate themselves actively in the Industry 5.0 environment. In the framework herein developed, human-centric, smart, and lean are complementary aspects, not three totally separate entities.

CHAPITRE 5 CONCLUSION AND RECOMMENDATIONS

5.1 Summary of works

The present thesis sought to provide a review of research for exploring the opportunities of XR and lean and constructing preliminary collaboration for EoL disassembly planning in the industrial era where Industry 4.0 and 5.0 coexist. Disassembly planning is an essential area of end-of-product-life management. The disassembled items represent business opportunities, consisting of constituent parts or subassemblies that are potentially recoverable and serviceable. However, most disassembling operations are laborious manual activities. Importantly, intrinsic issues, such as incomplete product life-cycle information and highly uncertain EoL conditions, make EoL disassembly planning more complex. Together with the existing extrinsic challenges (e.g., compulsory environmental rules and scheduling demands) in times of prevailing uncertainty, a one-fold mathematical formulation might not be the best solution. Hence, the current exploration of EoL disassembly planning entails paradigmatic shifts and detailed enablers from managerial and techno-functional perspectives. The advent of a technology-driven revolution, Industry 4.0, prompted numerous digitalized initiatives and the active utilization of emergent technologies with the aims of improving efficiency and productivity in a cyber-physical system manner. The new revolution, Industry 5.0, concerns societal and industrial transformation simultaneously. Industry 5.0 is a natural evolution considering the next digital adoption cycle of a manufacturing/production system that is human-centric, sustainable, and resilient. By presenting the research progress and achievements in XR-assisted disassembly, lean disassembly, and XR-lean collaborations under the impacts of Industry 4.0 and Industry 5.0, respectively, the outlook on EoL disassembly concludes that the joint integration of XR and lean can offer a more sustainable future with advantageous initiatives of these two manufacturing paradigms. Overall, this study aims to enrich the literature on digital disassembly transformation and unfold the impact of XR-lean collaboration on disassembly planning through two structured and content-based literature reviews, along with an actionable research agenda and an integrated structure.

The summary of works can be broken into three parts, as described below.

In accordance with two articles (Chapter 3 and 4), the first original contribution is analyzing and reporting the status, tendencies, and prospects of EoL disassembly planning in the context of Industry 4.0 and Industry 5.0. Two studies systematically presented review findings on the evolutionary vein of manufacturing paradigms (Industry 4.0 and Industry 5.0), especially in the context of EoL disassembly planning. Moreover, the resemblance and diffe-

rentiation among Industry 5.0, Industry 4.0, and Society 5.0 in past literature are discussed to gain a clearer understanding of the transition.

The second contribution was to establish a collaboration channel for XR and lean in EoL disassembly research. Two core enablers, XR and lean, are jointly integrated throughout the entire research analysis. Instilling XR and lean into EoL product disassembly planning is worthy of exploration because advancing technological and managerial implications is an ongoing pursuit for sustainable development. This thesis considers them as a distinctive unit playing crucial roles in assisting and supporting disassembly planning systems. The study also investigates their implementation paths and potential applications as preliminary work for future research. In the comprehensive context of digitally enabled adoptions, XR is representative and unique, thus appointed as an applied and impacted technology in this study. The functionality of XR allows users to visualize representations of physical objects in a 3D virtual format and a real-time mode. XR technologies are particularly relevant to the core of Industry 4.0 at the technical system level. XR serves as the primary means for playing its techno-functional role to accelerate the deployment of Industry 4.0 and Industry 5.0 perspectives. In other words, XR is considered as a technology relevant to both Industry 4.0 and Industry 5.0 simultaneously. As a widely-used and relatively mature production management approach, lean is applied in this study to reframe and accommodate digitalization. As a managerial philosophy, lean is irreplaceable. It can guide not only operational excellence of manufacturing and production systems towards cost-effective solutions but also emphasize human safety and well-being in businesses and organizations. Thus, the potential elements of lean principles and tools that can collaborate with XR were exploited in this study. Based on our findings from two systematic content-based review articles, XR–lean integration has the potential to improve the digitalization, quality, and effectiveness of EoL disassembly planning.

The third contribution consisted in developing a tailored agenda and an integrated conceptual framework to characterize the association of XR and lean in Industry 4.0 and Industry 5.0, identifying their benefits, challenges, and trends. Even though the first Industry 4.0-based agenda, SDSP, considered to unpack the human-centric perspective and envisioned the wave of Industry 5.0 phenomenon. However, SDSP depends on the XR–lean integration with Industry 4.0 initiatives emphatically. In the second article, the synergies jointly created by Industry 5.0, XR, and lean were transformed to their descriptive essences : human-centric, smart, and lean (HSL). By HSL, this study analyzed the theoretical components with the interaction with XR and lean, and examined potentials of their applications on the personality and characteristics of human being. Because this thesis focuses on emergent concepts and gaps, it is expected that the two contributing articles will arouse lively discussions and de-

bates in the domains of advanced computer-aided manufacturing, sustainable manufacturing, computer science, industrial marketing, and technological society.

5.2 Limitations and future research directions

Envisioning Disassembly 5.0 Envisioning Disassembly 5.0 can be a directional topic since "Disassembly 4.0" [54] was ever proposed to offer reference value. XR has the sufficient capacity to merge virtual space with physical spaces compared to other digital technologies. Moreover, XR is open and flexible to cooperate with CPS, DT, and AI to carry out complex virtual-physical problems. However, an Industry 5.0-based system should have more active executions in multi-technology integration and multi-systems heterogeneity manners. Recent studies are rarely geared towards the techno-functional development in the era of Industry 5.0. To build up more collaboration channels, future research can explore more key enabler technologies to positively impact the sustainable development of EoL disassembly planning.

The survival of lean in a new revolutionary adoption cycle Even though there is a wealth of evidence showing that lean can coexist with Industry 4.0, lean in Industry 5.0 is still in an immature stage, both in practice and in academic research. From a futuristic perspective, the pathway of turning lean into practical reality in the next revolutionary adoption cycle can be an issue. The successful implementation of lean management aimed at achieving operational excellence might not be the only choice. The directional route of developing organizational or enterprise culture can be an evolutionary track.

Heterogeneous system integration Since the inception of Industry 5.0, some recent heterogeneous systems have received scant attention in the literature. Under the impact of Industry 5.0, all heterogeneous systems should consider human-centric traceability. However, if implementing multi-technology devices, data processing can become highly complex. It is necessary to propose more novel structures or frameworks to solve the difficulties confronted by Industry 5.0.

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