Demystifying the digital transition of remanufacturing: a systematic review of literature

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Demystifying the Digital Transition of Remanufacturing: A Systematic Review of Literature

ABSTRACT

The remanufacturing sector has already instigated the shift towards the adoption of digital technology, especially enabled by the progressive development of the Industry 4.0 (I4.0) technologies. However, remanufacturing systems are faced with many challenges that are not typically found in traditional manufacturing systems. Inspired by the need to better understand their idiosyncrasies, particular needs and implications, this paper aims to scrutinise current issues and concerns about digital transformation in the remanufacturing systems. In particular, the paper reviews the extant literature to observe: (1) how the I4.0 technologies have so far been used in remanufacturing and (2) the benefits and risks that need to be considered by remanufacturers when adopting the I4.0 technologies. We have elucidated the significance of our findings and subsequently synthesised our thoughts into eight propositions that demystify the mechanisms of how the I4.0 technologies can bring potential benefits when used by remanufacturers to accomplish a portfolio of remanufacturing tasks, and the risks they need to be aware of. This articulation represents contributions to knowledge as it will set out the underpinning of the future human-technology collaboration, which is key in the I4.0 realm.

Keywords: Remanufacturing; Industry 4.0; Internet of Things; Systematic Literature Review.

List of abbreviations:

I4.0: Industry 4.0
AM: Additive Manufacturing
AR: Augmented Reality
BDA: Big Data Analytics
CC: Cloud Computing
Cobots: Collaborative robots
CPS: Cyber-Physical Systems
DDS: Data-Driven Simulation
EoL: End-of-Life
IoT: Internet of Things
OEM: Original Equipment Manufacturer
RFID: Radio Frequency Identification
SLR: Systematic Literature Review
VR: Virtual Reality

1. INTRODUCTION

Remanufacturing is a comprehensive and rigorous industrial process by which previously sold, worn, non-functional, or end-of-life (EoL) products, also called 'cores', are recovered and transformed into functional products that at least match the performance of newly manufactured products (Hamzaoui-Essoussi & Linton, 2014). Amongst the many alternatives to product recovery options such as reuse, refurbishment or recycling, remanufacturing is deemed the most unique, as the considerable value from used products will be retained through extension of the product lifetime (Charnley et al., 2019). This allows remanufactured products to have new and multiple life cycles (San-Francisco et al. 2020; Östlin et al., 2009) with incremental upgrades. Remanufacturing also plays a crucial role in reverse logistics (Jukun et al., 2008; Wen-hui et al., 2011) allowing the global transition towards a circular economy (Matsumoto et al., 2016; Singhal et al., 2020) and sustainable development (Gunasekara et al., 2018).

Remanufacturing processes comprise a number of complex and often sequential activities, including core acquisition, parts harvesting, disassembly, cleaning, inspection, reassembly, refurbishing, reselling, and some combinations of those activities (Lundmark et al., 2009; Savaskan et al., 2004). The remanufactured products are then rebuilt to the specifications of the original equipment manufacturers (OEMs) (King et al., 2006) using a combination of used/repaired parts with some brand-new parts before they undergo a thorough product testing. As the aim is to restore products to 'as-new' condition (Garrido-Hidalgo et al., 2019), spare parts or components that cannot be refurbished to the original quality and specification are replaced (Goepp et al., 2014). Remanufacturing may also feature product upgrades by adding and improving parts or components that are prone to failure.

Remanufacturing systems inherit a high level of uncertainty and complexity compared to traditional manufacturing systems (Gallo et al., 2012). Most often, there is no sufficient information about the location (Wang & Wang, 2017), condition or the amount of core supply. Predicting the parts that could be reused, replaced or repaired, as well as the complexity of the required remanufacturing tasks, hence cost, can be challenging. Sometimes, similar cores with a similar acquisition (buy-back) cost may require different spare parts and repair tasks, making the prediction of the recovery cost difficult (Fang et al., 2016). Reprocessing activities and inventory control are also difficult due to the small batch size. Remanufacturing companies also often find it difficult to convince their customers to buy the remanufactured products due to their perceived quality and reliability of the remanufactured products (Lundmark et al., 2009). Novel solutions and management alternatives are thus crucial to reduce those challenges and uncertainties in the adoption of advanced remanufacturing processes.

The advancement of the Industry 4.0 (I4.0) technologies, e.g. Internet of Things (IoT), Radio Frequency Identification (RFID), Big Data Analytics (BDA), Collaborative robots (Cobots), Data-Driven Simulation (DDS), can unlocks opportunities and offers new and innovative solutions to remanufacturing (Butzer et al., 2016; Yang et al., 2018). IoT, for instance, was reported to have enabled real-time scheduling of car engine remanufacturing, so it can increase efficiency in resource management (Zhang et al., 2018). Another example is demonstrated by the adoption of RFID to improve inventory control, operational efficiency, and data visibility at the collection, disassembly and refurbishing centres, within the reverse logistics networks (Kumar et al., 2015). Similarly, BDA has also been used to assist quality-dependent collection mechanisms in firms that combine new products and remanufactured products in their business model (Xu et al., 2019). Cobots with an active control scheme were also reported to enable a semi-automatic dismantling of automotive water pumps by human operators and robots, thus avoiding collisions and potential human injuries (Huang et al., 2019). Recently, DDS combined with RFID technologies were employed to predict material flow behaviour using an adaptive simulation model to reflect changes in remanufacturing operations (Goodall et al., 2019).

Inspired by the need to better understand their idiosyncrasies, particular needs and implications, this paper aims to investigate the factors affecting the uptake of the I4.0 technologies in remanufacturing, that will ultimately answer the following research questions:

RQ1: How have I4.0 technologies enabled the digital transition of remanufacturing?

RQ2: What are the opportunities and benefits from digital transition in remanufacturing, as well as the limitations and risks posed by it?

The answers to the above questions were sought through a systematic review of the literature, whose findings were synthesised into eight propositions that provides a fundamental underpinning of future human-technology collaboration and cooperation, which is key to the success of I4.0 technologies adoption.

2. MATERIALS AND METHODS

In fulfilling the aim of the research, this paper adopts the Systematic Literature Review (SLR) as the research method. When conducted properly, the SLR provides traceable, evidence-based outcomes (Denyer & Tranfield, 2009), allowing the state-of-the-art I4.0 technologies and remanufacturing research to be contextualised systematically via the thematic analysis. The steps involved in the SLR are described below.

2.1. Step 1: Planning the review

Before conducting the review, we carried out a scoping study to outline the boundaries of the subject area. We recognised remanufacturing as a general research theme that could be investigated from several perspectives. We emphasised our particular interest is to understand how I4.0-enabled capabilities can contribute to the remanufacturing industry. Therefore, we developed a rigorous review protocol exploring the hypotheses and reasons to incorporate I4.0 technologies in the remanufacturing systems.

2.2. Step 2: Conducting the review

Our comprehensive search began with the selection of databases hosting scientific journal papers, conference proceedings, books, etc. We decided to use the three biggest electronic databases (Web of Science, EBSCO and Scopus) to ensure the widest possible coverage of the research domain. Search strings were then created, taking into account relevant terms, keywords, their synonyms and acronyms. Additionally, we combined search strings using AND and OR Boolean operators inside a search formula, in order to generate a replicable outcome from the search query. Table 1 shows the search strings and the search formula used.

Table 1: Search strings and search formula

Code	Formula for search query
SS1	"Industry 4.0" OR "Industrie 4.0" OR "Fourth Industrial Revolution" OR "Digital manufacturing" OR "Digital automation"
SS2	"Cyber physical system" OR "Additive manufacturing" OR "Big Data" OR "Augmented Reality" OR "Cloud computing" OR "Internet of Things" OR "Radio-Frequency Identification"
SS3	"Remanufactur*" OR "Re-manufactur*" OR "Recondition" OR "Retrofit" OR "Refurbish" OR "Overhaul" OR "Rebuild" OR "End-of-Life"
SF	(SS1 OR SS2) AND SS3 AND LT (LANG) AND LT (YEAR) AND LT (DOCTYPE)

Legend: SS – Search String; **SF** – Search Formula; **LT** – Limited to; **LANG** - English; **YEAR** – from 2009 to 2021; **DOCTYPE** = Articles, conference/proceedings papers.

We then developed two sets of inclusion criteria for quality assessment (Denyer & Tranfield, 2009) considering a broader spectrum of qualified publications from 2009 to 2021, as follows:

Title and abstract screening:

1. Peer-reviewed articles, conference/proceedings papers only;
2. Only articles written in English;
3. The purpose of the article, the finding, and/or the implication is pertinent to I4.0 technology applications in remanufacturing systems.

Full-text screening:

1. The contribution to knowledge is relevant in terms of importance and significance;
2. Theoretical base is acceptable having practical rationales for study to some extent;
3. Justified research design with, at least, acceptable proxies for economic variables;
4. The focus of the article is relevant to the I4.0 technology in remanufacturing.

By applying the review protocol in Figure 1, in total, 83 papers were included in the SLR (see Appendix).

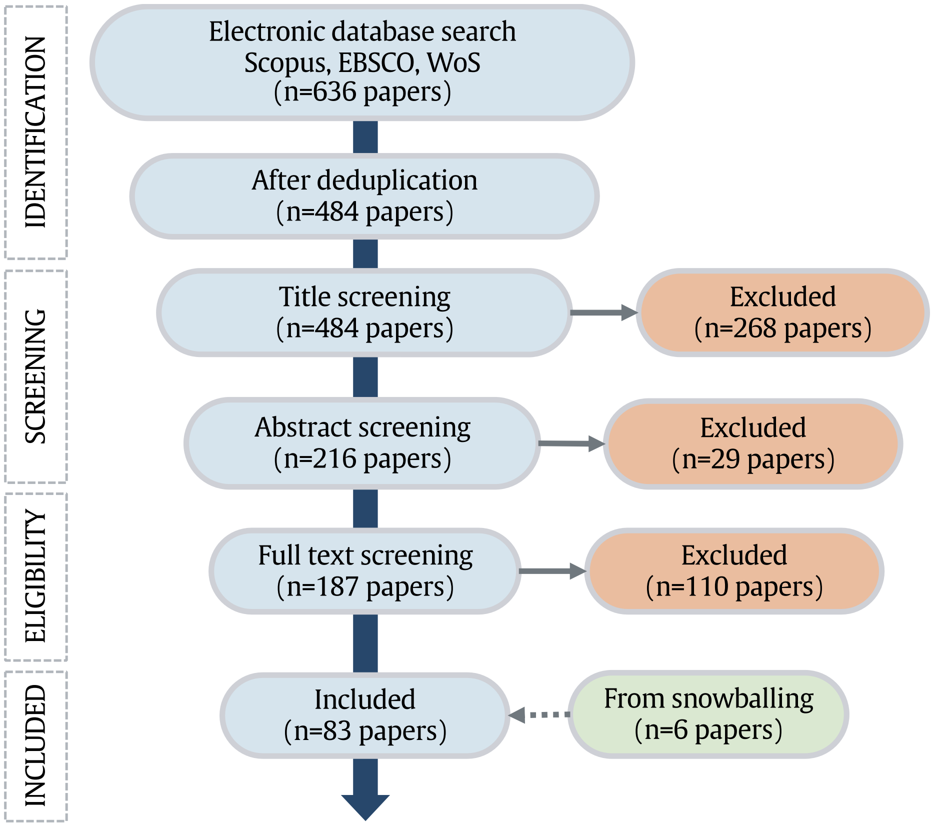

Figure 1: Review protocol to select SLR dataset

A coding scheme was subsequently developed to help the systematic data extraction and content analysis. By running the cycles of coding, we were able to extract chunks of data from the papers that subsequently formed the research themes. In the first coding cycle, our goal was to identify the relevant data segments to be coded. Thus, we screened each paper to obtain some insights about the opportunities and risks of adopting the I4.0 technologies in remanufacturing, and to identify coding patterns at the same time. In the second coding cycle, we clustered the coded data into a number of categories. The idea was to capture some specific elements (i.e. definitions, challenges, features, etc.) and to develop a sense of categorical, thematic and concept definition guiding a theoretical organisation of data collected during the first coding cycle. During the third coding cycle, we reanalysed and reorganised the coded data. This stage included quality checking by comparing the codes. This led us to clustering the coded data into a number of themes. Figure 2 summarises our coding scheme and themes generation.

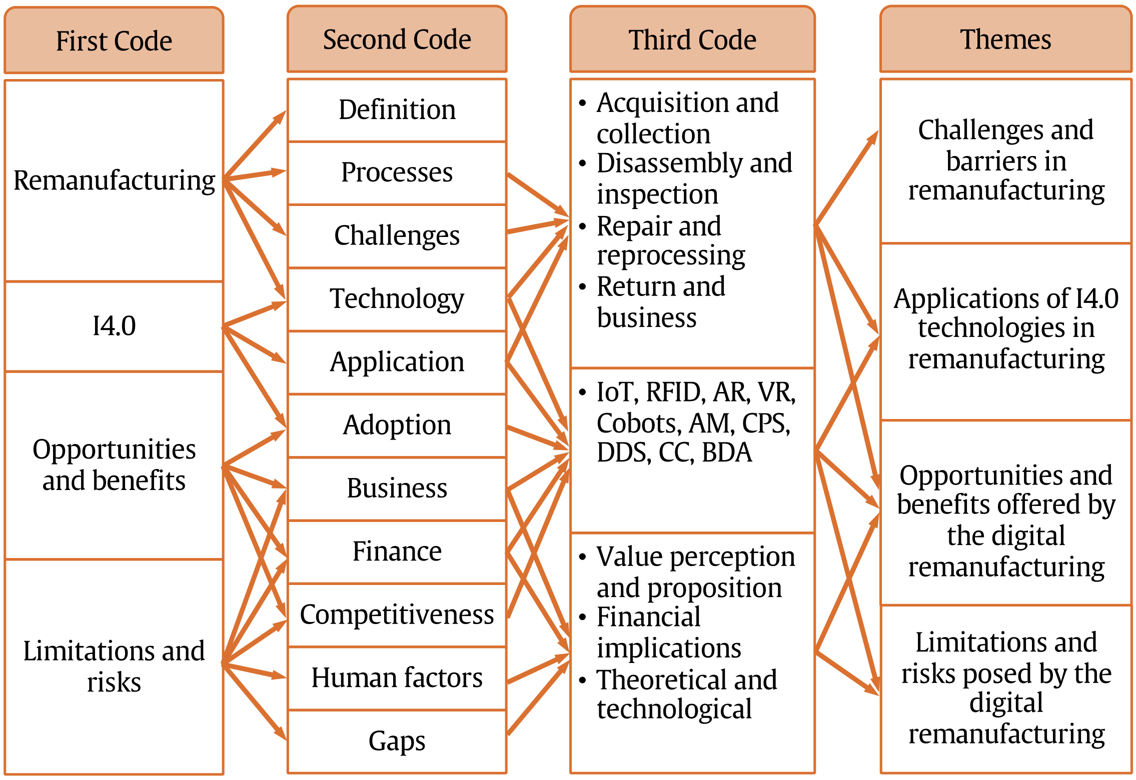

Figure 2: Coding scheme and theme generation

2.3. Step 3: Documenting the review

The documentation follows strict scientific procedures for empirical research. We described in detail the extraction of relevant data, content analysis to derive the research findings and synthesis of the research propositions. We discussed the theoretical underpinning that showed the principal concepts, which were fundamental to understanding the research themes. Those tasks were undertaken in a structured way in order to answer the research questions.

3. THEMATIC ANALYSIS

3.1. Theme 1: Challenges and barriers associated with remanufacturing systems

Remanufacturing of used product, as a product recovery practice, has gained substantial importance among EoL product initiatives (Yang et al., 2018). Taking into account the growing pressure to reduce waste generation by strengthening sustainable development policies, manufacturing companies are looking for solutions to reduce loss and raw material usage through refurnishing used parts based on the condition of returned products (Fang et al., 2016).

In this scenario, remanufacturing seems to be feasible option to allows EoL products and parts to be commercialised again as a new product (Lee et al., 2017) and returning a used product to a serviceable condition (Sundin & Bras, 2005; Yeo et al., 2017).

Despite this valuable solution for EoL products, the remanufacturing industry continues to face many challenges and barriers. In a business model where customers become core suppliers, used products could come from various consumers (Joshi & Gupta, 2019) and from different locations (Bag et al., 2020; Cao et al., 2011; Lundmark et al., 2009) requiring an appropriate reverse logistics scheme (Thürer et al., 2019). Very often, consumers do not have enough knowledge about remanufacturing (Wang et al., 2014) making the return rate in some companies (such as electronics consumers) consistently low (Ullah & Sarkar, 2020). Similarly, the acquisition and collection of used products depends not only on customers, but also on the quantity of the products which were sold in previous periods (Fang et al., 2016). However, neither quality nor quantity can be easily predicted, making product recovery procedures uncertain (Ondemir & Gupta, 2014b) in such a way that identical products can be different in quality (Cao et al., 2011). In fact, variability in quality, quantity and timing in remanufacturing systems often leads to variable lot sizes (Lundmark et al., 2009; Yang et al., 2018).

Disassembly, cleaning and inspection are subsequent stages after acquisition and collection of used products (Zhang et al., 2018). Used products are disassembled and all modules and parts are extensively inspected (Xu et al., 2019) to determine core status and condition (Goodall et al., 2019), material and spare parts needed (Butzer et al., 2016), recovery cost and reprocessing routines. In particular, recovery cost, which depends on what components should be replaced, repaired or reused (Fang et al., 2016), must be between 40% and 65% of a comparable new product (Lee et al., 2017), thus determining which product must be remanufactured or sent for recycling (Tsao et al., 2017). Unfortunately, the condition of core and parts is usually unknown until the used products are disassembled and inspected (Wang et al., 2018). As the majority of remanufacturing is not performed by OEMs but rather by third party companies with no collaboration (Yang et al., 2018) or information sharing (Parlikad & McFarlane, 2009), reverse engineering is frequently necessary to determine product specification and characteristics (Sundin & Bras, 2005) making disassembly a labour-intensive task (Lundmark et al., 2009; Yeo et al., 2017). For this reason, disassembly and inspection operations are still dependent on *ad hoc* experience (Yang et al., 2018; Siew et al., 2020) requiring technically skilled engineers and technicians (Wang et al., 2018).

Unpredictable core conditions, supply and demand also make production planning and control problematic for the remanufacturing industry (Butzer et al., 2016). Since EoL products' status and conditions are not identical (Alqahtani et al., 2019), a recovery plan (Joshi & Gupta, 2019) with different material (Zhang et al., 2018), spare parts and reprocessing routines (Yeo et al., 2017) must be elaborated for each product. Additionally, numerous work orders with particular recovery requirements should be attended to at the same time in the remanufacturing facilities (Butzer et al., 2016), leading to enormous pressure and variation on product recovery scheduling (Ondemir & Gupta, 2014a). For this reason, production planning and control becomes even more difficult in remanufacturing (Cao et al., 2011) with complicated inventory management and variable processing times caused by unknown core conditions (Lundmark et al., 2009). Thus, the process of remanufacturing is complicated by uncertainties in timing, by the quality and quantity in terms of inventory control, the design of product, and production planning of the remanufactured product (Lee et al., 2017).

Redistribution, reselling and return of remanufactured product can also affect remanufacturing business models. As long as there are no established definitions and standards for remanufactured product in various sectors (Yang et al., 2018), quality assurance definition, which is highly dependent on the quality of EoL product received, is difficult to achieve (Ondemir & Gupta, 2014b). Sometimes, warranty policies relatively consistent with those of new and used products may not be financially viable for remanufacturers (Alqahtani et al., 2019). Customers are not convinced of the value of remanufactured products (Sundin & Bras, 2005) or are not willing to pay a similar new-product price for remanufactured products (Yang et al., 2018). This can reduce the expected profit margin and discourage product recovery (Zhang et al., 2018) causing uncertainty in the demand for remanufactured products (Lundmark et al., 2009). Product market managers do not incorporate remanufacturing products into their strategic selling plan (Birkel et al., 2019). Again, when refurbishment is executed by independent remanufacturers rather than OEMs, there is no information sharing between them (Matsumoto et al., 2016) with no incentive or collaborative environment (Wang et al., 2014).

***Finding 1**: There are numerous challenges and barriers faced by the traditional remanufacturing systems related to the acquisition, collection, evaluation and reprocessing of cores, resulting in poor prediction of incoming cores (and spare parts) and their quality, and the difficulty in matching the supply and demand. These challenges and barriers hinder the uptake of remanufacturing.*

3.2. Theme 2: Applications of I4.0 technologies in remanufacturing systems

From our dataset, we identified some evidence of the applications of the I4.0 technologies. For instance, IoT and RFID have interchangeably been investigated to support products (Fang et al., 2016) and materials (Främling et al., 2011) tracking, tracing and real-time monitoring (Främling et al., 2009; Trappey et al., 2010; Saygin & Tamma, 2012). The capability to retrieve information with IoT/RFID support track and trace of used products (Kumar & Chan, 2011) and resources (Zhou & Piramuthu, 2013) in the entire supply chain. IoT/RFID has also been applied to optimise the acquisition strategy for used products (Fang et al., 2016), to increase the return rate of electronic products (Kumar & Chan, 2011; Ullah & Sarkar, 2020), to digitalise waste collection systems (Popa et al., 2017; Thürer et al., 2019) and also to evaluate design alternatives for EoL products (Joshi & Gupta, 2019). In addition, some researchers have dedicated their work to evaluate the economic impact of RFID adoption in remanufacturing (Kumar & Chan, 2011), to assist the data-driven simulation approach (Goodall et al., 2019; Lu et al., 2019), to schedule production in real-time (Zhang et al., 2018), to measure the quantitative impact of offering warranties with cost (Alqahtani et al., 2019), to manage quality in product recovery (Ondemir & Gupta, 2014b) and to retrieve item-level product information (Zhou & Piramuthu, 2013).

Some I4.0 technologies were particularly devoted to assist used product recovery activities. Augmented Reality (AR) and Virtual Reality (VR) have been used to train workforce (Ceruti et al., 2019), by supplying real-time information about the work environment (Rüßmann et al., 2015), and guiding them on disassembly operations (Butzer et al., 2016; Kerin & Pham, 2019) or even on maintenance execution (Zenisek et al., 2017). Those technologies seem to be particularly useful to assist disassembly and inspection operations which are done manually (Siddiqi et al., 2019) and are still dependent on ad hoc engineers' experience (Yang et al., 2018). Furthermore, Cobots have been researched to automate the dismantling of EoL products (Huang et al., 2019) where possible, and set up to safely interact with human operators and other robots for component handling and inspection (Ruggeri et al., 2017).

Additive Manufacturing (AM) and 3D printing have been highlighted as important enabling technologies for part repair (Zhang et al., 2019) and reuse or to produce customised parts. Unlike traditional manufacturing processes (which are based on material removal mechanisms), in AM processes, materials are added layer upon layer to manufacture the parts (Ceruti et al., 2019; Knofius et al., 2019). Using the AM technology, replacement parts and components can be made at anytime and anywhere, as needed, enabling timely repair or refurbishment of worn parts and components (Cooper, 2014). Current literature recognises AM as an important enabling technology to repair automotive components (Yusoh et al., 2020) and high value avionic (Ceruti et al., 2019) and naval (Cooper, 2014) components. Some researchers have also dedicated their work to understanding the additive and subtractive manufacturing combination (Le et al., 2018a; 2018b) allowing the reuse of EoL products (Strong et al., 2019) and avoiding material recycling (Le et al., 2017). From a business model perspective, researchers have also considered total cost of consolidation (Knofius et al., 2019), cost model (Xu & Feng, 2014), mapping drivers and barriers (Matsumoto et al., 2016), life cycle assessment (Böckin & Tillman, 2019), thus balancing the benefits and implications of AM technological support in remanufacturing.

Some I4.0 technologies have been dedicated to the provision of additional production planning, inventory control and decision-making assistance. Such technologies involve horizontal integration among remanufacturing sectors with real-time information sharing among players. Cyber-Physical Systems (CPS) and DDS were highlighted as disruptive technologies for decision making in remanufacturing systems. In particular, CPS synergises the physical and virtual worlds to enable the connection between physical operations and computing/communication infrastructures (Herterich et al., 2015; Lu, 2017). Butzer et al. (2016), Kerin & Pham (2019) and Lu et al. (2019) recognised the importance of CPS in remanufacturing, however, none of them have explicitly demonstrated its applications in remanufacturing. We found only one study proposing an architecture of an energy cyber-physical system enabled management for energy-intensive manufacturing industries to promote the implementation of a cleaner production strategy (Ma et al., 2019).

Most literature from our dataset utilised simulation to leverage real-time data to reflect the physical world of remanufacturing processes in a virtual environment. The combination of discrete-event simulation with IoT/RFID technologies seems to be one of the popular research interests in remanufacturing. Our sample includes simulation for process planning within an engine remanufacturing plant (Lu et al., 2019), to diagnose a waste collection system (Popa et al., 2017), to understand material flow in remanufacturing (Goodall et al., 2019), to analyse the warranty of EoL products (Alqahtani et al., 2019), for decision support electric motors recovery (Kumar & Chan, 2011), for commercial and operational decisions in a power transformer remanufacturing plant (Teixeira et al., 2019) and to quantitatively examine vehicle component recovery benefits (Parlikad & McFarlane, 2009). Simulation has generated a lot of interests in remanufacturing research due to its inherent capabilities to evaluate complex scenarios and situations (Tozanlı et al., 2020).

The Cloud Computing (CC) technology enables centralised computing, flexible data storage and scalable services capabilities (Wang & Wang, 2017). It delivers various computing services over the Internet (Li et al., 2015) offering a core infrastructure, platform, software and storage capability (Kireev et al., 2018a). CC has been combined with other enabling technologies (such as IoT, RFID) for integration and information sharing among players. Extensive literature has used CC platforms, architectures and pooled resources to increase collection levels (Popa et al., 2017), cloud services (Wang & Wang, 2017) and shared resources (Thürer et al., 2019) to benefit waste collection and remanufacturing. Furthermore, cloud platforms support the capabilities of self-awareness, self-organising, self-adaptive and self-comparison for green manufacturing models (Ma et al., 2019) and also information systems (Dev et al., 2020) for monitoring, remote management and maintenance of engineering systems (Kireev et al., 2018b).

BDA has been recognised as an enabler for extracting meaningful value from remanufacturing system data. Predictive analytic systems can capture valuable insights about customers and products and their usage (Ali et al., 2018; Ehret & Wirtz, 2017; Kireev et al., 2018a), help marketing teams to attract target consumers (Bressanelli et al., 2018), predict and map market demand (Neto & Dutordoir, 2020; Wang et al., 2020) or even to increase sales and return rates (Xiang & Xu, 2019). BDA is an important solution to monitor individual product lifecycle stages (Bressanelli et al., 2018) that helps deal with uncertainty in the scheduling activities (Dinis et al., 2019) and at the same time ensures an efficient use of data in IoT applications (Ali et al., 2018). BDA also allows the redesign of internal and external business strategies (Lowenstein & Slater, 2018) by intelligently excluding used products with low or no value for remanufacturers, hence improving core assessment quality (Xu et al., 2019), and enabling predictive repair of engineering systems (Kireev et al., 2018b).

Finding 2: *The extant literature presents numerous applications of I4.0 technologies (used individually or combined) in remanufacturing, especially to (1) track materials and used products, (2) assist waste collection activity, (3) better support for used product evaluation, (4) facilitate rescheduling and dynamic decision making on remanufacturing facility, (5) capture potential consumers and core suppliers* *aiming to increase remanufactured products sales and return rate respectively. However, an integrated and holistic view mapping those key enabling technologies within the remanufacturing process seems to be lacking.*

3.3. Theme 3: Opportunities and benefits from the digitalisation of remanufacturing systems

Some research reported advances in the retrieval of used products with I4.0 technologies. That evidence falls within: (1) better management of customer relations, (2) real-time tracking and monitoring capabilities, (3) quality-dependent acquisition and (4) increased collection levels. For instance, better customer preferences and perception about remanufactured products can be achieved with CPS support (Yeo et al., 2017). With real-time monitoring capabilities provided by IoT/RFID, remanufacturers could easily retrieve used product information from external OEM databases (Alqahtani et al., 2019), or products' lifecycle data (Fang et al., 2016) determining the actual conditions of products and components (Joshi & Gupta, 2019). Remanufacturing companies can better execute EoL product collections based on real-time information provided by IoT (Bressanelli et al., 2018). Additionally, IoT and CC have shown a great potential to increase the collection levels of various waste-type products (Popa et al., 2017) no matter how far or geographically dispersed they are (Cao et al., 2011). Quality dependent acquisition can become feasible since products in the market can be tracked and traced with IoT/RFID (Fang et al., 2016) whereas BDA provide the exclusion of poor-quality products with no value for remanufacturers (Xu et al., 2019).

Used product evaluation is fundamental to determining recovery cost and plan. It involves disassembly, cleaning and inspection activities looking for parts that should be reused or replaced. Most often those activities are manual and involve *ad hoc* technical skills. AR can be used to support works with target information about products or components to be disassembled (Butzer et al., 2016). In particular, human and robot collaboration for disassembly could enable catering for the effects of uncertainties in the condition of those products and unpredictability in remanufacturing operations (Huang et al., 2019). IoT/RFID provide new insights and possibilities about used product monitoring (Alqahtani et al., 2019) to estimate the remaining useful life of components (Ondemir & Gupta, 2014b), and making customised diagnoses at item levels (Zhou & Piramuthu, 2013). Using IoT solutions, product lifecycle data can be captured and used to determine the conditions of and recovery operations for EoL products (Joshi & Gupta, 2019) providing insights about which components should be reused or replaced (Bressanelli et al., 2018).

The I4.0 enabling technologies (such as IoT/RFID, data-driven simulation and additive manufacture) are particularly useful to aid the repair and reprocessing routines. Again, IoT/RFID real-time tracking and monitoring capabilities have been mentioned as useful in gathering product specification information (e.g., lead time or product sequence) for better production and inventory management (Fang et al., 2016; Ondemir & Gupta, 2014b) in real-time (Butzer et al., 2016), thus helping to reduce inconsistences and ambiguities in the planning of remanufacturing operations (Alqahtani et al., 2019). In addition, IoT/RFID combined with data-driven simulation could support better decision making when assessing the benefits and risks of strategies for production scheduling (Popa et al., 2017) providing a rapid evaluation mechanism and quick process assessment through data-driven simulation (Lu et al., 2019; Okorie et al., 2020). From part repair or spare part production, additive manufacture has been pointed out as particularly useful for remanufacturing (Strong et al., 2019). Combining additive and subtractive manufacturing could avoid material recycling using EoL parts (Le et al., 2018a) and create a new life or new usage in their lifecycle (Le et al., 2018b) that ultimately reduce material and resource consumptions (Cezarino et al., 2021; Kravchenko et al., 2020). It could also be particularly useful for high asset value (such as in aerospace companies) to produce complex parts (French et al., 2019; Le et al., 2018a).

Some I4.0 enabling technologies have supported redistribution, reselling and remanufacturing business decisions. For instance, IoT/RFID has been used to gain more insight about products and customers during the use phase (Alcayaga et al., 2019). Those enabling technologies provide a great opportunity to attract target consumers (Bressanelli et al., 2018) and to offer more after sales services (Fang et al., 2016). BDA and CC can enable better management of product information, guiding towards collaborative (Xu et al., 2019) and advanced (Yeo et al., 2017) decision making in remanufacturing, which accelerates the process of returns, improves brand image, and promotes the sustainable development of companies (Xu & Feng, 2014). Similarly, IoT/RFID can help manufacturers to understand how to include remanufacturing in their product portfolio (Yeo et al., 2017) with economic and environmental incentives for remanufacturing (Ondemir & Gupta, 2014a; Zhou & Piramuthu, 2013). Furthermore, IoT/RFID can supply credible information about product lifetime based on real data (Ingemarsdotter et al., 2019; Ondemir & Gupta, 2014b), helping remanufacturers to better predict warranty policies and periods (Alqahtani et al., 2019) for remanufactured products. Table 2 summarises the opportunities for and benefits of digitalisation of remanufacturing systems.

Finding 3: *The I4.0 technologies can make new or existing remanufacturing processes more efficient through the application of real-time access of used product data, on-demand manufacturing of customised parts and provision of remote skill support. In this way, the I4.0 technologies potentially lead to cost savings across the entire value chain, helping remanufacturing companies to better target their customers, and determine the appropriate level of warranty, as well as the terms and conditions of selling.*

Table 2: Opportunities for and benefits of digitalisation of remanufacturing systems

Remanufacturing process	**I4.0 Technologies**	**Main opportunities and benefits**
Acquisition, collection	IoT, RFID, CC, BDA	(1) Capability to obtain actual conditions of used products; (2) Improve collection levels and procedures; (3) Quality dependent acquisition; (4) Better execution of EoL collections
Disassembly, cleaning, inspection	AR, VR, Cobots, RFID, IoT	(1) Guide used product disassembly; (2) Reduce variability in disassembly lead time; (3) Better estimation of product lifetime; (4) Customised diagnosis at item level; (5) Additional support for product recovery plan
Repair and reprocessing	RFID, IoT, DDS, CPS, AM	(1) Better production control and inventory management; (2) Better decision-making assessment; (3) Support for dynamic scheduling; (4) Used product parts recovery; (5) Avoid EoL product recycling; (6) Customised production of complex parts
Redistribution, reselling, return and business model	IoT, RFID, BDA, CC	(1) Attract target customers; (2) Improve brand image; (3) Promote sustainable development; (4) Possibility of including remanufacturing in company's portfolio; (5) Novel solutions for after sales; (6) Better understand how product has been used; (7) More information sharing between stakeholders.

Legend: RFID – Radio Frequency Identification; IoT – Internet of Things; BDA – Big Data Analytics; AM – Additive Manufacturing; VR – Virtual Reality; AR – Augmented Reality; Cobots – Collaborative Robots; CC – Cloud Computing; CPS – Cyber-Physical Systems; DDS – Data-Driven Simulation

3.4. Theme 4: Limitations and risks of digital remanufacturing systems

Notwithstanding the obvious opportunities that come from the digitalisation of remanufacturing systems, we should also recognise some obstacles and risks it imposes. Those obstacles were collected, coded and then clustered into: (1) value perception and proposition, (2) financial implications and (3) theoretical and technological limitations.

From the value perception and proposition perspective, we must recognise that market shift for sustainable production and consumption depends on how well I4.0 can support sustainable value proposition (de Man & Strandhagen, 2017). Advanced economies tend to promote I4.0 enabling technologies with different levels and rates (Rüßmann et al., 2015) whilst less industrialised countries might suffer from a strong pressure to acquire competitive advantages (Lee et al., 2017). Even though I4.0 enabling technologies can better offer product information, value perception and proposition can only be achieved under certain conditions and premises (Ehret & Wirtz, 2017) with more benefits for some particular remanufacturing sectors (Yeo et al., 2017). Consumers often do not accept remanufactured products that they feel risk becoming obsolete or unfashionable (Sundin & Bras, 2005). Furthermore, no matter how much I4.0 enabling technology we have, core supply and demand can be unstable (Lu et al., 2019) and still dependent on customer behaviour and perception respectively (Thürer et al., 2019). Likewise, intellectual property rights issues might affect the relationship between remanufacturers and OEMs (Siddiqi et al., 2019) with legal grey areas of activities regarding analysis of third-party products for information retrieval and remanufacturing (Stark et al., 2014).

Financial implications also influence the practical application of I4.0 enabled technologies in remanufacturing. Currently, there is no full understanding about the costs (Stark et al., 2014) and barriers (Isaksson et al., 2018) faced in expanding digitalisation in remanufacturing. Some economic issues about investments and equipment acquisition costs (Kumar & Chan, 2011), operationalisation (Yeo et al., 2017), and competing standards and privacy concerns (Leonard, 2014; Tsao et al., 2017) are not clarified properly. For some companies, RFID devices (Kumar & Chan, 2011) and AM machines (Knofius et al., 2019) could be a high-risk investment. Despite the recognised importance of evaluating advanced enabling technologies from an economics perspective (Kumar & Chan, 2011), sometimes there is no available historical data about remanufacturing processes or techniques with which to measure cost estimation (Xu & Feng, 2014). No matter how much enabling technology we have, there will always be a compromise between acquisition, recovery and new product manufacture costs (Fang et al., 2016).

Theoretical and technological limitations also cause problems for the digital transition of remanufacturing systems. Currently, there is no consensus about standards and definitions, or non-modular set-up (de Man & Strandhagen, 2017), for remanufactured products in various sectors (Yang et al., 2018). So far, just a few studies have been dedicated to evaluating methodologies used to implement RFID technologies (Cao et al., 2011; Tsao et al., 2017) or to measuring the impact on reverse logistics (Kumar et al., 2015), and reverse supply chain management (Zhou & Piramuthu, 2013) has not been well understood. Likewise, IoT standards, data formats (Ali et al., 2018), and scope of application in remanufacturing (Charnley et al., 2019) are limited, requiring an extra effort for international procedures, criteria and investigation. Since there is no definite self-adaptability solution and also limited demonstration or application of the data-driven simulation (Goodall et al., 2019; Okorie et al., 2020), its implementation in small-and medium-sized remanufacturing companies remains challenging (Lu et al., 2019). This issue has become more critical especially when links between industry and academia are weak (Butzer et al., 2016), causing the complexity in adopting the I4.0 solutions for the remanufacturing sector (Kerin & Pham, 2020). Table 3 summarises the limitations and risks of digital remanufacturing.

Finding 4: *High initial investment costs with no full understanding of standards and privacy concerns may result in financial risks and poor return on investment, as customer perceptions and value propositions may vary and do not generate sufficient incentives for transition to digital remanufacturing. Furthermore, remanufacturers may doubt the true benefits arising from the digitalisation of remanufacturing systems, due to the limited number of successful industrial cases.*

Table 3: Limitations and risks of digital remanufacturing

Limitations and risks	**Description**
Value perception and proposition	(1) Perception may vary at different levels and rates in remanufacturing; (2) Depends on how well enabling technology can support sustainable value; (3) Core supply can still be unstable; (4) Intellectual property with information sharing among manufacturers/remanufacturers

Financial implications	(1) No full understanding about costs; (2) High equipment costs and initial investments; (3) Competing standards, privacy concerns and scope of application; (4) No available historical data for cost estimation; (5) Additional support for product recovery plan
Theoretical and technological limitations	(1) No consensus about standards and definitions; (2) Few studies on practical applications; (3) Standards and data format; (4) Absence of methods to integrate heterogeneous data; (5) Limited techniques and applications; (6) few studies exploring emerging I4.0 technologies in remanufacturing.

4. SYNTHESIS OF THE PROPOSITIONS

Our research questions aim to delve into the determinants for the digital transition in remanufacturing and to unveil evidence-based characteristics collated from various insights, evidenced by our findings presented in the previous section. Following those findings, in this section we synthesise our thoughts in order instigate future academic discourse in this emerging field of research.

4.1. Demystifying the relevance of I4.0 technologies in remanufacturing

Our findings have revealed many challenges and barriers curbing the adoption of digital remanufacturing. Unless the technologies afford the essential needs of the remanufacturers, then the remanufacturers are less likely to shift to digital remanufacturing. We hereby explain the association between the I4.0 technologies and the remanufacturers who uses the technologies to complete the remanufacturing tasks.

For instance, the IoT/RFID technologies may be adopted by the remanufacturers not only to intelligently identify the locations of the cores (Cao et al., 2011) but also to interrogate information embedded in the cores (i.e., location, condition, lifetime, etc.) which is key to appraising the core quality. BDA offers the remanufacturers the capability to monitor customer demand (Ali et al., 2018; Kireev et al., 2018b) and products with lifetime monitoring capabilities (smart products), so as to improve the quality of forecasting, hence increased matching between supply and demand.

Proposition 1: *In core acquisition and collection, IoT/RFID, and BDA technologies can remotely locate and individually evaluate core conditions, leading to an* *enhanced supply and demand matching and a quality-driven core acquisition strategy.*

Cobots sharing the same workspace with the human operators can boost the productivity of the disassembly and cleaning tasks (Huang et al., 2019). This semi-automated disassembly process is particularly desirable since the process can be complicated, depending on the condition of the cores. On-the-job support as well as product disassembly, cleaning, and inspection instructions from the OEMs or specialists can be delivered by the less experienced technicians using AR and/or VR technologies (Butzer et al., 2016). AR and VR combined with Artificial Intelligence (e.g. machine learning) allows capturing best practices in an interactive and continuous learning mechanism. In this way, it can potentially reduce the dependence on human decision making and improve on-the-job, specialised training (Ceruti et al., 2019), making it possible to accelerate the assessment tasks of the incoming core, resulting in a more robust outcome of product recovery cost and routines.

Proposition 2: *In disassembly, cleaning and inspection, Cobot technologies will enable semi-automatic core disassembly; AR and VR will enable the provision of virtual instructions guiding the EoL product evaluation. Cobots, AR and VR can significantly reduce human/skill dependence and uncertainty in spare parts and reprocessing routines, leading to a more precise recovery cost estimation.*

The combination of CPS, DDS, RFID, IoT, and AM can revolutionise the digital production control and inventory management. Since the product and component lifetime is known in advance, remanufacturers can prepare the required spare parts and reprocessing tasks just-in-time. Linking physical devices with virtual components (as digital twins) allows the detection of abnormal events, conditions and unforeseen circumstances in real-time (Lu, 2017). Using online simulation (Teixeira et al., 2012) as the backbone of the digital twins, production data and asset conditions allow periodic synchronisation between the remanufacturing plant and its virtual representation, thus increasing the accuracy of experimentation as a result of the dynamics modifications and real-time scheduling in a virtual environment (Teixeira et al., 2019). Similarly, the AM technology can be used to produce customised parts, be they from scratch or from worn out parts, on-demand (Cooper, 2014), reducing the effort in managing a high value spare parts inventory.

Proposition 3: *In repair and reprocessing, CPS, DDS, AM, RFID, IoT technologies will allow real-time scheduling, and the provision of on demand, customised parts, leading to better production planning and inventory control. These technologies can significantly reduce uncertainty in reprocessing routines.*

Redistribution, reselling, and return of remanufactured products can all benefit from CC, BDA, RFID and IoT. CC, BDA, and IoT connect consumers and providers (Bressanelli et al., 2018) in a long-term relationship, helping the remanufacturing industry to increase after-sales markets and services (Fang et al., 2016; Ondemir & Gupta, 2014b). Similarly, RFID/IoT technologies can also contribute to designing more effective warranty terms based on the individual component lifetime (Alqahtani et al., 2019). With IoT/RFID technologies, remanufacturers can precisely estimate selling price and warranty period, reducing the possibility of contract penalties. Also, those enabling technologies can provide more effective information sharing between OEM and independent remanufacturers (Fang et al., 2016) creating a collaborative environment where remanufactured products and new products will not compete with each other but reach their own specific market niche.

Proposition 4: *In reselling, redistribution, and return, IoT/RFID technologies can be used to carry out the assessment of the remaining useful life of components; CC and BDA allow easy access to potential consumers and information sharing, leading to improved selling and data analytics usage to identify target markets, avoiding new and remanufactured product cannibalisation.*

4.2. Recognising the inhibitors to digital remanufacturing

Even though the I4.0 will reshape the future of many industrial sectors, we identified some inhibitors to the digitalisation of the remanufacturing system. These inhibitors are considered as forces (or risks) that can be viewed from the six perspectives: economic, social, environmental, technological, legal and political.

From the economic perspective, remanufacturing companies may be risk-averse to the digital transformation when they do not have a clear understanding of expenses, financial expenditure, or even period of amortisation (Birkel et al., 2019). This is particularly critical for those enabling technologies that require high initial investment (such as IoT, RFID and AM), training costs, and intensive IT-related transformations (Lu et al., 2019; Tsao et al., 2017; Tuptuk & Hailes, 2018). It could become even more complex in a collaborative environment where the financial investment required for digitalisation must come from multiple partners. Moreover, a detailed return on investment analysis must consider specific scenarios and business conditions to better estimate costs, expenses and benefits. Many small- and medium-sized remanufacturing companies (particularly those with a low level of automation) will face a drastic change in their facilities and business model (Birkel et al., 2019). For these companies, digital transformation could lead to substantial replacement of many existing assets and legacy systems. As a consequence, they can lose their core competence with long-term investment returns making digitalisation unfeasible.

Demand for mass customisation could also bring some additional risks for the remanufacturing business model. Since it is expected there will be an increase in pressure for better performance prices and costs, there is no absolute guarantee that remanufacturers will adapt their managerial practices quickly (Badri et al., 2018) to meet current market demand. Similarly, digital remanufacturing companies could face many difficulties in convincing consumers to buy remanufactured products if the price is the same as the brand-new products (Xu et al., 2019) or if the remanufactured products were originated from highly customised ones. To provide an appropriate level of digital transition, the remanufacturing industry should strike a balance between customisation and standardisation so as not to make the remanufacturing business model unviable. Furthermore, there is no clear explanation or related studies on how digital automation will affect the remanufacturing business model in many industrial sectors and segments.

***Proposition 5*:** *The transition to digital remanufacturing requires an in-depth economic analysis in terms of the evaluation of initial investment, responsibilities, adaptability, flexibility, customisation, and automation levels, and consequently, this will help remanufacturers to balance the opportunities and risks of digitalisation.*

From the social perspective, it is expected there will be a great impact in terms of a significant decrease in low-skilled (Cezarino et. al, 2021), highly standardised jobs as they are replaced by cyber-physical systems (Bonekamp & Sure, 2015). It could become even more critical for older workers, since they would not adapt as easily to using some enabling technologies (such as AR, VR and Cobots). For this particular workforce, it is expected there will be more resistance to sharing their workspace, or learning from a virtual avatar that teaches them how they should execute their work routines. With digital transformation, it is expected that the workforce will acquire a wide range of competences, combining conventional oriented task expertise with computer skills (Badri et al., 2018).

Remanufacturers should be aware that the potential environmental benefits accrued from the digitalisation of remanufacturing may be offset by the ecological impacts arising from the digital transition. For instance, since the majority of the existing remanufacturing processes are manual or with low level of automation (Siddiqi et al., 2019), shifting to digital remanufacturing could also mean a considerable consumption of raw material to produce hi-tech equipment and machines, increased energy consumption and CO2 emission, along with the needs for high power computational systems. Thus, traditional remanufacturers could be risk-averse from the I4.0 technologies if they perceive that the benefits would negatively affect their ecological brand image.

Proposition 6: *The transition to digital remanufacturing requires social and environmental considerations, particularly in ensuring workforce acceptance of digitalisation, and at the same time, ensuring the balance between the environmental benefits and additional materials, energy consumption and carbon emission.*

The transition towards the digital era will also expose remanufacturing systems to technological hazards and pitfalls. A gradual transition can be expected as the integration between new and legacy systems is not yet well understood. Furthermore, manufacturers, remanufacturers and partners must work together to establish unified standards, common interfaces and intellectual property limits for information sharing. The use of cloud computing technologies could expose organisations to cyber-attacks. More investment in cyber-security capabilities is required (Wu et al., 2018) to support the design practices for multiple product lifecycles. Additionally, some enabling technologies (such as AM, Cobots, AR, etc.) are still in their infancy with few business implications and rare industrial case studies in remanufacturing (Kerin & Pham, 2019). Once the remanufacturers start their digital transformation, they will be more dependent on information and communication technologies, as well as software solutions. In fact, there are more questions than answers from both industry and academia when it comes to adopting digital technology in remanufacturing (Butzer et al., 2016).

Proposition 7: *The transition to digital remanufacturing requires a detailed technical appraisal on new and legacy system integration, standards and interface definitions, information sharing, data security issues, business implications and industrial case studies. The appraisal allows traditional remanufacturers to balance the opportunities and risks of digital transition.*

The remanufacturing industry must also consider the legal aspects involved in digital transition. Since product design information must be shared between manufacturers/remanufacturers to facilitate the design for remanufacturing (Fofou et al., 2021), data protection, intellectual property and customer/product usage data regulations are crucial to avoid any conflict of interest. Customers may be reluctant to accept the way in which their personal and product data are used (Leonard, 2014) by the remanufacturers. This could significantly impact the remanufacturing business model. Another open issue is concerned with working with robots that requires the development of health and safety rules regulating the human/machine collaboration.

Political will and policy management are fundamental to creating the appropriate environment for digital transition. A suitable infrastructure (e.g. high-speed Internet and sufficient energy supply) (Birkel et al., 2019) is necessary. Appropriate policies are needed to enable the product life extension, so as to increase motivation of the remanufacturers to invest on digital transition. Furthermore, without the right policies, remanufacturers may not be attracted to collaborate with others, for instance in the design for remanufacturing, information sharing of the product specification, etc., making the true benefits of digital transition difficult to achieve.

Proposition 8: *The transition to digital remanufacturing requires an understanding of jurisdictional and legal aspects, such as data protection, intellectual property, working time, and customer privacy. Likewise, political will and policy management are crucial to the establishment of an appropriate infrastructure and business environment to facilitate the digital transition.*

5. CONCLUSIONS AND FUTURE WORK

Our research aims to expand actual knowledge about digital transformation within remanufacturing systems. We have presented the current challenges and barriers in remanufacturing systems and elaborated the I4.0 enabling technologies to overcome them. Additionally, we have evaluated the opportunities and benefits of digitalisation in remanufacturing systems as well as the limitations and risks posed by it. Those investigations resulted in four findings summarising our thematic analysis. Even though there exists much research that maps the transition of conventional manufacturing to the digital manufacturing systems, the majority of that research does not consider specific aspects of the remanufacturing business model. Without this, it will be challenging for the remanufacturing industry to balance the benefits and opportunities against limitations and risks arising from digitalisation.

Our research has shown where and how the prominent I4.0 enabling technologies have so far been used in remanufacturing systems. We elucidated the significance of our findings and synthesised our thoughts into eight propositions to guide academics and practitioners on the transition to digital remanufacturing systems. We believe that this articulation represents a significant contribution to knowledge as it might provide a fundamental underpinning of human-machine collaboration, which is key in the I4.0 realm.

As a trajectory for future research, we will carry out an empirical investigation to test the propositions in a real industrial setting. By doing so, we can emphasise the inclusion and consideration of the benefits and risks in the development of digital remanufacturing of the future.

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APPENDIX

Table A1. Studies included in the review

ID	Doc Type	Author	Title	Journal/Conference/Publisher	Source
1	AR	Cezarino et al., (2021)	Diving into emerging economies bottleneck: Industry 4.0 and implications for circular economy	Management Decision	SCP
2	CF	de Man & Strandhagen (2017)	An industry 4.0 research agenda for sustainable business models	Procedia CIRP	WOS
3	CF	Ceruti et al. (2019)	Maintenance in aeronautics in an industry 4.0 context: The role of augmented reality and additive manufacturing	Journal of Computational Design and Engineering	SCP
4	CF	Stark et al. (2014)	Advanced technologies in life cycle engineering	Procedia CIRP	WOS
5	AR	Li et al. (2015)	Ecodesign in consumer electronics: Past, present, and future	Critical Reviews in Environmental Science and Technology	SCP
6	CF	Isaksson et al. (2018)	Digitalisation, sustainability and servitisation: Consequences on product development capabilities in manufacturing firms	Proceedings of NordDesign	SCP
7	AR	Bressanelli et al. (2018)	Exploring how usage-focused business models enable circular economy through digital technologies	Sustainability	WOS
8	CF	Cooper (2014)	Laser-based additive manufacturing: where it has been, where it needs to go	Laser 3D Manufacturing	WOS
9	AR	Fang et al. (2016)	Optimization for a three-stage production system in the Internet of Things: procurement, production and product recovery, and acquisition	The International Journal of Advanced Manufacturing Technology	WOS
10	AR	Tuptuk & Hailes (2018)	Security of smart manufacturing systems	Journal of Manufacturing Systems	WOS
11	CF	Zenisek et al. (2017)	Smart maintenance lifecycle management: A design proposal	29th European Modeling and Simulation Symposium	SCP
12	CF	Herterich et al. (2015)	The impact of cyber-physical systems on industrial services in manufacturing	Procedia CIRP	SCP
13	AR	Knofius et al. (2019)	Consolidating spare parts for asset maintenance with additive manufacturing	International Journal of Production Economics	SCP

14	CF	Kireev et al. (2018b)	Predictive repair and support of engineering systems based on distributed data processing model within an IoT concept	6th International Conference on Future Internet of Things and Cloud Workshops	SCP
15	CF	Främling et al. (2011)	Intelligent products in real-life applications	International Conference on Industrial Engineering and Systems Management	WOS
16	AR	Ehret & Wirtz (2017)	Unlocking value from machines: business models and the industrial internet of things	Journal of Marketing Management	EBS
17	CF	Butzer et al. (2016)	Identification of approaches for remanufacturing 4.0	IEEE European Technology and Engineering Management Summit	WOS
18	AR	Yang et al. (2018)	Opportunities for industry 4.0 to support remanufacturing	Applied Sciences	WOS
19	CF	Yeo et al. (2017)	Revolutionizing technology adoption for the remanufacturing industry	Procedia CIRP	SCP
20	AR	Zhang et al. (2018)	The 'Internet of Things' enabled real-time scheduling for remanufacturing of automobile engines	Journal of Cleaner Production	WOS
21	AR	Wang & Wang (2017)	A cloud-based production system for information and service integration: an internet of things case study on waste electronics	Enterprise Information Systems	WOS
22	AR	Wang et al. (2018)	A comprehensive survey of ubiquitous manufacturing research	International Journal of Production Research	WOS
23	CF	French et al. (2019)	Transfer analysis of human engineering skills for adaptive robotic additive manufacturing in the aerospace repair and overhaul industry	Advances in Manufacturing, Production Management and Process Control	SCP
24	AR	Popa et al. (2017)	Smart city platform development for an automated waste collection system	Sustainability	WOS
25	CF	Främling et al. (2009)	From tracking with RFID to intelligent products	IEEE Conference on Emerging Technologies & Factory Automation	WOS
26	AR	Wu et al. (2018)	Cybersecurity for digital manufacturing	Journal of Manufacturing Systems	WOS
27	AR	Ali et al. (2018)	Design methodology of microservices to support predictive analytics for IoT applications	Sensors	EBS
28	CF	Kireev et al. (2018a)	Cloud computing in housing and utility services monitoring systems	6th International Conference on Future Internet of Things and Cloud Workshops	SCP
29	AR	Wang et al. (2014)	A cloud-based approach for WEEE remanufacturing	CIRP annals	SCP
30	AR	Goodall et al. (2019)	A data-driven simulation to support remanufacturing operations	Computers in Industry	SCP

31	AR	Zhang et al. (2019)	A hybrid process integrating reverse engineering, pre-repair processing, additive manufacturing, and material testing for component remanufacturing	Materials	SCP
32	AR	Kerin & Pham (2019)	A review of emerging industry 4.0 technologies in remanufacturing	Journal of Cleaner Production	EBS
33	AR	Huang et al. (2019)	A strategy for human-robot collaboration in taking products apart for remanufacture	FME Transactions	SCP
34	AR	Xu & Feng (2014)	Develop a cost model to evaluate the economic benefit of remanufacturing based on specific technique	Journal of Remanufacturing	SCP
35	AR	Kumar et al. (2015)	Economical impact of RFID implementation in remanufacturing: a Chaos-based Interactive Artificial Bee Colony approach	Journal of Intelligent Manufacturing	EBS
36	AR	Dev et al. (2020)	Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance	Resources, Conservation and Recycling	SCP
37	AR	Siddiqi et al. (2019)	Low cost three-dimensional virtual model construction for remanufacturing industry	Journal of Remanufacturing	SCP
38	AR	Ullah & Sarkar (2020)	Recovery-channel selection in a hybrid manufacturing-remanufacturing production model with RFID and product quality	International Journal of Production Economics	SCP
39	AR	Zhou & Piramuthu (2013)	Remanufacturing with RFID item-level information: Optimization, waste reduction and quality improvement	International Journal of Production Economics	EBS
40	AR	Strong et al. (2019)	Rethinking reverse logistics: role of additive manufacturing technology in metal remanufacturing	Journal of Manufacturing Technology Management	SCP
41	AR	Xu et al. (2019)	The influence of big data system for used product management on manufacturing–remanufacturing operations	Journal of Cleaner Production	SCP
42	AR	Matsumoto et al. (2016)	Trends and research challenges in remanufacturing	International Journal of Precision Engineering and Manufacturing-Green Technology	SCP
43	AR	Charnley et al. (2019)	Simulation to enable a data-driven circular economy	Sustainability	SCP
44	AR	Kumar & Chan (2011)	A superiority search and optimisation algorithm to solve RFID and an environmental factor embedded closed loop logistics model	International Journal of Production Research	SCP
45	AR	Ingemarsdotter et al. (2019)	Circular strategies enabled by the internet of things - A framework and analysis of current practice	Sustainability	SCP
46	AR	Tsao et al. (2017)	Closed-loop supply chain network designs considering RFID adoption	Computers & Industrial Engineering	SCP

47	AR	Xiang & Xu (2019)	Dynamic cooperation strategies of the closed-loop supply chain involving the internet service platform	Journal of Cleaner Production	SCP
48	AR	Joshi & Gupta (2019)	Evaluation of design alternatives of End-of-Life products using internet of things	International Journal of Production Economics	SCP
49	AR	Le et al. (2018a)	Extracting features for manufacture of parts from existing components based on combining additive and subtractive technologies	International Journal on Interactive Design and Manufacturing	SCP
50	AR	Ondemir & Gupta (2014b)	Quality management in product recovery using the Internet of Things: An optimization approach	Computers in Industry	SCP
51	AR	Alcayaga et al. (2019)	Towards a framework of smart-circular systems: An integrative literature review	Journal of Cleaner Production	SCP
52	AR	Parlikad & McFarlane (2009)	A Bayesian decision support system for vehicle component recovery	International Journal of Sustainable Manufacturing	SCP
53	AR	Ondemir & Gupta (2014a)	A multi-criteria decision making model for advanced repair-to-order and disassembly-to-order system	European Journal of Operational Research	EBS
54	AR	Böckin & Tillman (2019)	Environmental assessment of additive manufacturing in the automotive industry	Journal of Cleaner Production	SCP
55	AR	Trappey et al. (2010)	Genetic algorithm dynamic performance evaluation for RFID reverse logistic management	Expert Systems with Applications	EBS
56	AR	Thürer et al. (2019)	Internet of Things (IoT) driven kanban system for reverse logistics: solid waste collection	Journal of Intelligent Manufacturing	SCP
57	AR	Cao et al. (2011)	Knowledge-enriched shop floor control in end-of-life business	Production Planning and Control	SCP
58	CF	Lowenstein & Slater (2018)	Management of test utilization, optimization, and health through real-time data	IEEE AUTOTESTCON	SCP
59	AR	Le et al. (2017)	Process planning for combined additive and subtractive manufacturing technologies in a remanufacturing context	Journal of Manufacturing Systems	SCP
60	AR	Lu et al. (2019)	An IoT-enabled simulation approach for process planning and analysis: a case from engine re-manufacturing industry	International Journal of Computer Integrated Manufacturing	SCP
61	AR	Garrido-Hidalgo et al. (2019)	An end-to-end internet of things solution for reverse supply chain management in industry 4.0	Computers in Industry	SCP

62	AR	Ma et al. (2019)	Energy-cyber-physical system enabled management for energy-intensive manufacturing industries	Journal of Cleaner Production	EBS
63	AR	Saygin & Tamma (2012)	RFID-enabled shared resource management for aerospace maintenance operations: a dynamic resource allocation model	International Journal of Computer Integrated Manufacturing	SCP
64	AR	Le et al. (2018b)	The development of a strategy for direct part reuse using additive and subtractive manufacturing technologies	Additive Manufacturing	SCP
65	AR	Leonard (2014)	Customer data analytics: privacy settings for 'Big Data' business	International data privacy law	SCP
66	AR	Dinis et al. (2019)	Valuing data in aircraft maintenance through big data analytics: A probabilistic approach for capacity planning using Bayesian networks	Computers & Industrial Engineering	SCP
67	AR	Lundmark et al. (2009)	Industrial challenges within the remanufacturing system	Proceedings of the 3rd Swedish Production Symposium	SNO
68	AR	Yusoh et al. (2020)	Analysis of Automotive Component Design for Reparation using Additive Manufacturing Technology	International Journal of Integrated Engineering	WOS
69	AR	Wang et al. (2020)	Big data driven Hierarchical Digital Twin Predictive Remanufacturing paradigm: Architecture, control mechanism, application scenario and benefits	Journal of Cleaner Production	SCP
70	CF	Kravchenko et al. (2020)	Circular economy enabled by additive manufacturing: Potential opportunities and key sustainability aspects.	Proceedings of NordDesign	SCP
71	AR	Bag et al. (2020)	Examining the role of procurement 4.0 towards remanufacturing operations and circular economy	Production Planning & Control	WOS
72	AR	Siew et al. (2020)	Human-oriented maintenance and disassembly in sustainable manufacturing	Computers & Industrial Engineering	WOS
73	AR	Teixeira et al. (2019)	Extending the decision-making capabilities in remanufacturing service contracts by using symbiotic simulation	Computers in Industry	SCP
74	AR	Lu (2017)	Industry 4.0: A survey on technologies, applications and open research issues	Journal of Industrial Information Integration	SNO
75	AR	Alqahtani et al. (2019)	Warranty and maintenance analysis of sensor embedded products using internet of things in industry 4.0	International Journal of Production Economics	SCP
76	RP	Rüßmann et al. (2015)	Industry 4.0: The future of productivity and growth in manufacturing industries	Boston Consulting Group	SNO

77	AR	Okorie et al. (2020)	Towards a simulation-based understanding of smart remanufacturing operations: a comparative analysis	Journal of Remanufacturing	SCP
78	AR	Neto & Dutordoir (2020)	Mapping the market for remanufacturing: An application of “Big Data” analytics	International Journal of Production Economics	WOS
79	AR	Östlin et al. (2009)	Product life-cycle implications for remanufacturing strategies	Journal of Cleaner Production	SNO
80	CF	Gunasekara et al. (2018)	Remanufacture for Sustainability: A review of the barriers and the solutions to promote remanufacturing	International Conference on Production and Operations Management Society	SNO
81	AR	Lee et al. (2017)	Remanufacturing: Trends and issues	International Journal of Precision Engineering and Manufacturing-Green Technology	SNO
82	AR	Kerin & Pham (2020)	Smart remanufacturing: a review and research framework	Journal of Manufacturing Technology Management	SCP
83	AR	Tozanlı et al. (2020)	Trade-in-to-upgrade as a marketing strategy in disassembly-to-order systems at the edge of blockchain technology	International Journal of Production Research	WOS

Legend: AR – Article; CF – Conference; RP – Report; WOS – Web of Science; SCP – Scopus; EBS – EBSCO; SNO – Snowballing