UNIVERSITY OF BIRMINGHAM
University of Birmingham Research at Birmingham

A review of emerging industry 4.0 technologies in remanufacturing

Kerin, Mairi; Pham, Duc

DOI:
10.1016/j.jclepro.2019.117805

License:
Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version
Peer reviewed version

Citation for published version (Harvard):
Kerin, M & Pham, D 2019, 'A review of emerging industry 4.0 technologies in remanufacturing', *Journal of Cleaner Production*, vol. 237, 117805. https://doi.org/10.1016/j.jclepro.2019.117805

Link to publication on Research at Birmingham portal

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 13. Oct. 2026

A Review of Industry 4.0 Emerging Technologies in Remanufacturing

Mairi Kerin [a], *, Duc Truong Pham [a]

[a] Department of Mechanical Engineering, School of Engineering, University of Birmingham, Birmingham B15 2TT, UK

* Corresponding author: Mairi Kerin, Mek790@student.bham.ac.uk

Abstract

This paper reviews the literature on the emerging digital technologies of Industry 4.0 (I4.0) focussed on the applicability of the Internet of Things (IoT), Virtual Reality (VR) and Augmented Reality (AR) in remanufacturing. Inspired by the frameworks developed to support exploration and realisation of I4.0 technologies for disassembly, the paper discusses the same emerging technologies in the wider context of remanufacturing. Trends and gaps have been identified from a value-creation perspective that encompasses the product to be remanufactured, the remanufacturing equipment and processes adopted and related organisation issues. Findings suggest there is a need to explore the connection of cyber-physical systems to the IoT to support smart remanufacturing, whilst aligning with evolving information and communication infrastructures and circular economy business models. The review highlights twenty-nine research topics that require attention to support this field.

Key Words: Industry 4.0; Virtual Reality; Augmented Reality; Internet of Things; Cyber-Physical Systems; Smart Remanufacturing

Abbreviations for Footnote

AI, Artificial Intelligence; AM, Additive Manufacturing; AR, Augmented Reality; BoL, Beginning of Life; CE, Circular Economy; CPS, Cyber Physical Systems; DCD, Data Carrying Devices; EI, Emerald Insight; EIS, Enterprise Information System; ELV, End of Life Vehicle; EoL, End of Life; ERP, Enterprise Resource Planner; GPS, Global Positioning System; HDOR, Heavy Duty Off-Road; HMI, Human-Machine Interface; ICT, Information Communication Technology; I4.0, Industry 4.0; IoT, Internet of Things; IR, Industrial Robot; IP, Intellectual Property; LCA, Life Cycle Analysis; MoL, Middle of Life; MRO, Maintenance Repair Overhaul; OEM, Original Equipment Manufacturer; PCB, Printed Circuit Board; PLC, Programmable Logic Controller; PLM, Product Lifecycle Management; PQ, ProQuest; PSS, Product Service Systems; PSST, Passive Self-Sensing Tags; QR, Quick Response; RFID, Radio Frequency Identification; SBoM, Service Bill of Material; SD, ScienceDirect; SME, Small-Medium Enterprise; VR, Virtual Reality.

1 INTRODUCTION

Remanufacturing is an important part of a circular economy. Through the remanufacturing of products, there are opportunities to increase the efficiencies of resources, reduce waste and support cleaner, more sustainable production, as demonstrated by Liu *et al.* (2014). Ijomah *et al.* (2007) provided a thorough review of the environmental and financial impact of increasing waste streams and influencing legislation, summarising case studies across the UK's manufacturing sectors evaluating the state of industry with respect to remanufacturing attitudes.

The definition of remanufacturing varies amongst industries. However, BS 8887-220:2010 is generally accepted with remanufacturing being the "steps required to change the product into as-new with at least equivalent performance and warranty of new" (British Standards Institution, 2010). This is the definition that will be adopted throughout this review. A key activity in remanufacturing is disassembly, reviewed by Chang *et al.* (2017a) who identified relevant emerging digital technologies including the Internet of Things (IoT), Virtual Reality (VR) and Augmented Reality (AR).

This state-of-art review identifies that there is no literature that explores specifically I4.0's emerging technologies in remanufacturing. Liu *et al.* (2016) wrote a paper titled "Remanufacturing in Industry 4.0" but their contribution to knowledge is minimum comparing I4.0 with blood circulation systems, citing only three other research papers. In contrast Alcácer and Cruz-Machado (2019) provide a thorough review of literature before setting out a road-map for I4.0 fulfilment in the manufacturing sector. However, this review is specific to manufacturing referring to remanufacturing only once. Additionally, the roadmap is completed to the conceptual level only and does not propose an extensive list of research topics as this review does. Similar in depth but from a big data analytics perspective, Ren *et al.* (2019) offer a comprehensive review into smart manufacturing and a products lifecycle, before coining the term 'sustainable smart manufacturing' that includes remanufacturing but is not exclusive to it. In contrast this review aims to fill a specific gap, that of the provision of research questions to allow a logical and complete approach to applying I4.0 to remanufacturing.

The digital transformation enabled by the emerging digital technologies is known as Smart Manufacturing or Industry 4.0 (I4.0), referred to within this text as I4.0. It is related to developments in cyber-physical systems (CPS) building on the three previous revolutions pertaining to mechanisation, electrification and information technology. CPS are mechanisms that are controlled or monitored by software integrating computers, networks and physical processes (Khaitan and McCalley, 2015). They are comprised of "smart machines, warehousing systems and factories that have been developed digitally and feature integrated end-to-end Information Communication Technology (ICT)… …This not only allows production to be configured more

flexibly but also taps into the opportunities offered by much more differentiated management and control processes" (Kagermann, 2013). This vision of an inter-connected factory that utilises IoT in the I4.0 future, is best illustrated by Schweichhart (2016).

The IoT is a "global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" (International Telecommunication Union, 2012). This networking of products through the IoT makes it possible to connect the entire manufacturing process converting factories with differentiated values streams, into smart environments (Stock and Seliger, 2016).

VR utilises computer generated images to enable users to view 3D products or environments, with AR an extension to this, overlaying computer-generated information onto real-world objects (Grier *et al.*, 2012). The remanufacturing sector is heavily reliant on manual processes (Butzer and Schötz, 2016). The utilisation of I4.0 and the IoT supported by VR and AR systems will be explored in this review to better understand how it may increase automation and thus the capability of this sector.

2 METHOD

As the I4.0 revolution is represented by the connectivity of machines, artificial intelligence (AI), big data and robots on the IoT (Park, 2017) and emerging digital technologies include I4.0 (or Smart Manufacturing), IoT, VR and AR (Chang *et al.*, 2017a), this collection of terms were used to search six databases to explore how they relate to remanufacturing (Figure 1). This systematic approach is used to allow for the process to be reproduced, a key quality when completing a review of this type Seuring and Gold (2012).

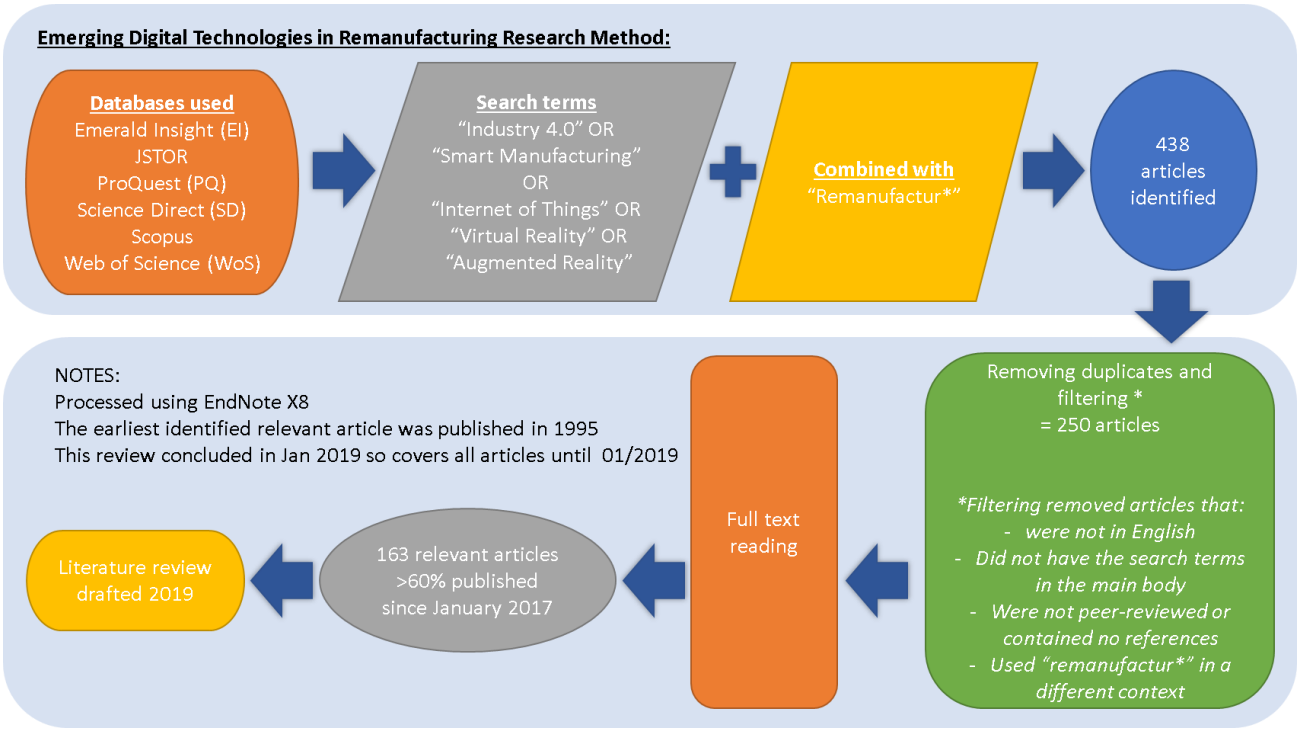


Figure 1 - Research Method

Full text reading revealed that the emerging technologies were intertwined to different extents within (re)manufacturing and there were gaps in the research. Overlaps in the material also existed. In order to provide uniform coverage without biases, the articles were categorised by 'value creation factor'. Those factors were utilised as it was the "interconnection of value creation networks in industry 4.0 [that] offers new opportunities for the realization of product life-cycles in closed circuit and industrial symbiosis" (Carvalho et al., 2018). Trends and opportunities to digitalise from supplier to customer using a 'value creation module' were presented by Stock and Seliger (2016) in their vision of integrated Industry 4.0 technologies in smart factories (Figure 2).

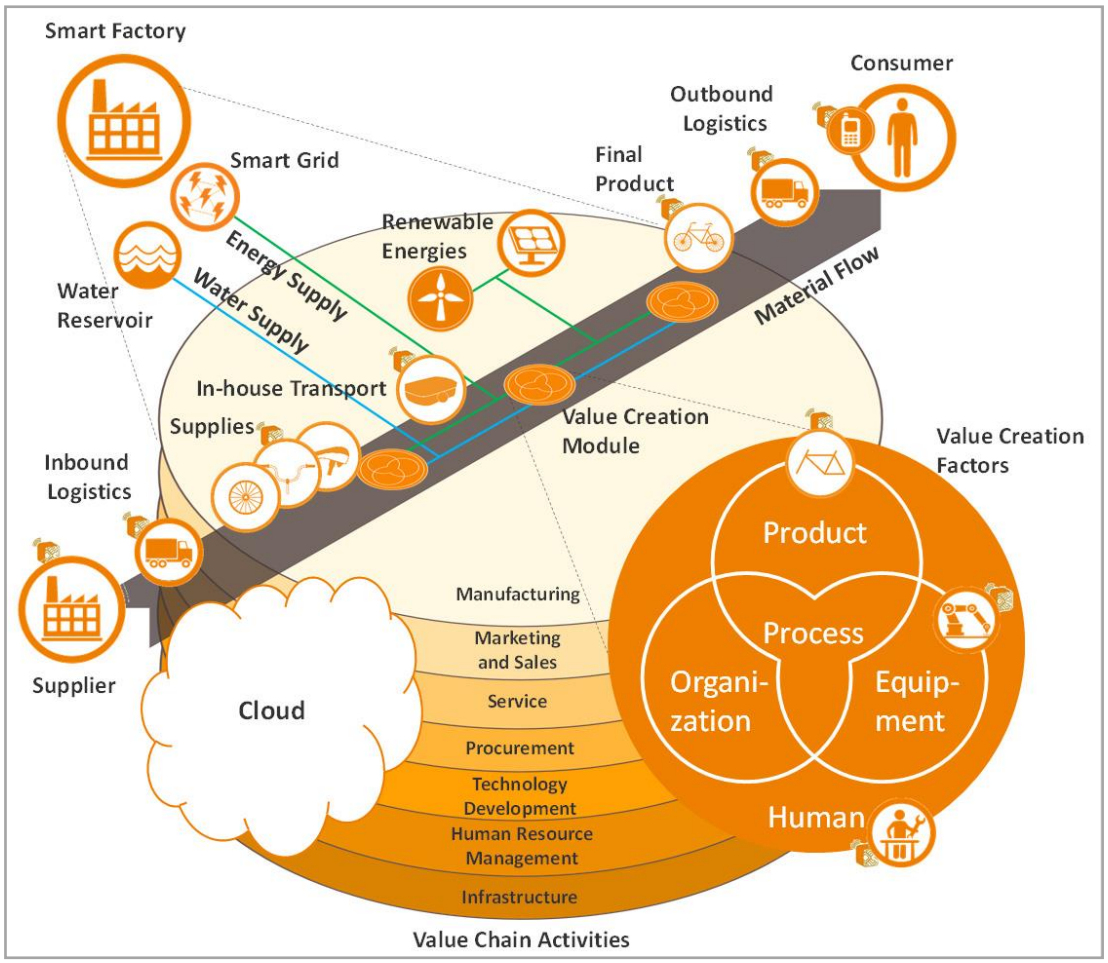


Figure 2 –The factors that form the Value Creation Module along the entire value chain (Stock and Seliger, 2016)

The value creation module was built on four factors: product, equipment, process and organisation (Stock and Seliger, 2016). These factors were used to categorise the articles discussed in this review to drive value creation in remanufacturing as follows: product (section 3), equipment (section 4), process (section 5) and organisation (section 6), with section 7 summarising research trends and gaps, drawing conclusions and recommendations for further work.

3 PRODUCT-RELATED WORK

This literature review identified two main streams of research emerging at product level for remanufacturing. 'Additive manufacturing (AM) for repair and replacement' and 'data carrying devices to support EoL processing'. Interestingly both streams are already found in manufacturing supporting the belief that the "capacity of industry 4.0 to really bring [sustainable practices including remanufacturing] to fruition… is largely due to the high level of virtualization, digitization and integration expressed by the technologies that exist today" (Carvalho *et al.*, 2018).

3.1 Additive Manufacturing (AM) for Product Repair and Remanufacture

Rejeski *et al.* (2018) explored AM with respect to the environment, recommending research into remanufacturing issues and opportunities of hybrid material and structures, customised products, and how intellectual property (IP) is managed. They suggested that thought must be given to a product at EoL for the wide-scale adoption of AM processes to be successful, a subject considered by Müller *et al.* (2018) who presented a demonstration tool for designers of AM products, to capture and display different lifecycle implications at the design stage. The flexibility of AM, along with its reliance on designs to be available digitally, means that it could also be used once a product is Middle-of-Life (MoL) to support rapid design modification should an unexpected failure or behaviour occur (Müller *et al.*, 2018), or for repair/remanufacturing activities providing aftersales services for companies employing product-service business models (Murmura and Bravi, 2018).

AM has the potential to contribute to sustainability through being combined with IoT technology but the full consequences of realising this are difficult to predict (Rejeski *et al.*, 2018). This is supported by Despeisse *et al.* (2017) who reviewed 3D printing with respect to the circular economy (CE), suggesting 3D printing had the potential to support sustainable manufacturing but questioned the current trajectory of adoption and whether the flexibility of the AM components complicated, rather than simplified, EoL processing. Reflecting on the integration of 3D printing with IoT and I4.0, they recognised the industrial landscape was already changing and concluded with a research agenda to evaluate issues and opportunities to achieving a CE. Yeo *et al.* (2017), on the other hand, identified a set of product characteristics (high-value, durable, with long technology cycles and the potential to be leased) where AM could be effectively implemented. They focused primarily on AM for component repair and the parallel introduction of the emerging digital technologies whilst offering a clear vision of a future factory for products with these characteristics, reviewing advanced manufacturing methods for remanufacturing.

3.2 Data Carrying Devices in Products to Support Remanufacturing

There were several data carrying devices (DCD) integrated with emerging digital technology discussed in the literature, the most popular being Radio Frequency Identification Tags (RFID). A thorough review of RFID in remanufacturing was presented by Ferrer *et al.* (2011). Issues with RFID are explored by Nowakowski (2018) using a case study to test capabilities and costs highlighting the effects of transmitter-responder distances, line-of-sight, and component material on signal strength, and 2D-code damage on readability and errors. Gao *et al.* (2013) employed an algorithm to optimise the arrangements of RFID systems to improve reliability to support remanufacturability assessments, but information on how this could be applied in industry was vague.

Other DCD included Quick Response codes (QR), 2D-codes (QR or Data Matrix) and Passive Self-Sensing Tags (PSST). Regardless of the DCD used, the systems generally target the same requirements, namely, the need to provide product data for real-time:

- monitoring and allocation of remanufacturing resources
- real-time MoL decision-making for End-of-Life (EoL) processing (remanufacture/dispose etc.)

3.2.1 DCD for Monitoring and Allocation of Resources

The use of DCD in remanufacturing is varied, with examples including the tracking of operators, resources, equipment and products through the value chain. Whilst the concept presented by Zhang *et al.* (2015) to utilise RFID and real-time data for dynamic optimisation of shop-floor material handling was for manufacturing, it is also applicable in remanufacturing. RFID was integrated with IoT and I4.0 for the tracking of reverse logistics vehicles (Liu *et al.*, 2018) and pallets (Tornese *et al.*, 2018) for real-time data-driven optimisation of resource and task allocation. RFID and the IoT were also used by Zhang *et al.* (2018a) to provide information on resource availability to support real-time production scheduling for an engine remanufacturer, similar to the works of Huang *et al.* (2017) who explored the using of RFID to build a dynamic holographic workshop map. While Gu *et al.* (2017) fitted RFID to Waste Electronic and Electrical Equipment (WEEE) to manage the product through repair or EoL processing, de Sousa Jabbour *et al.* (2018) suggested they could be used in the management of services such as water and power, whereas Yi and Park (2015) described the installation of a process controlled, IoT linked, multi-stage disassembly line for End-of Life Vehicles (ELV), with data collection that was remotely accessible. Using RFID tags on slave trolleys containing load cells, they linked the ELV to workstation instructions to drive process conformity and accurately monitor and report material weights.

3.2.2 DCD for MoL Decision-Making for End-of-Life (EoL) Processing

It was necessary to explore the use of the DCD to support MoL activities as the information gathered during this life phase may well assist EoL processing. A stand out example included Ness *et al.* (2015) who used RFID integrated with a stress sensor fitted to structural steel to assist in the reuse/remanufacture of EoL structural steel for new applications using Building Information Modelling and VR models. Presenting a theoretical case study, they evaluated potential environmental and business benefits, offering an insight into the range of applications of RFID for product level remanufacturing. A more detailed appraisal of the economic benefits of the use of DCD's and sensor-embedded in similar products is documented by Dulman and Gupta (2018) comparing wind turbine systems. Additionally, Stock and Seliger (2016) successfully demonstrated the retrofitting of an accelerometer and PLC to a MoL milling machine to form a CPS capable of interacting with others via IoT, providing a vision of intelligence upgrading for high-value, long-life products, but overall little consideration has been given to the connection of products already containing embedded or external

networking capability. These need to be considered as I4.0 relies on the interconnection of all networked products.

Air purifiers using passive RFID tags for internal data transfer integrated with sensors, read by mobile data systems, linked together in a web-based environment to share information to better support MoL and EoL activities, were the subjects of an extensive paper by Li *et al.* (2015). Musa *et al.* (2014) successfully demonstrated the integration of RFID, sensors and GPS into a single chip for MoL data transfer after a review of mobile Internet, GPRS, 4G, and RFID. "It can be said that the main benefits of these technologies are that they enable enterprises to be more coordinated or integrated, smarter, leaner, more agile, efficient and productive" (Musa *et al.*, 2014). However, they suggested a level of intelligence and decision-making was required to provide meaningful MoL information for remanufacturing, a subject that is rarely discussed but relevant, and adds further complexity to data management, reliance and product whole-life support. Additionally, the willingness of customers to participate in the collection of data along with the role that they play in data generation, collection and sharing is a concern (Field *et al.*, 2018).

Wang *et al.* (2014) presented an interesting and applicable novel architecture where a WEEE product labelled with a QR code filled with BoL/MoL data provides information to a cloud service. The system was aimed at engaging the consumer when a product is no longer required or fails. The user scans the QR code on the product triggering the upload of data, employing a web-based interface where a cloud service coordinator can cross-reference the demand and arrange the relevant EoL service (incl. remanufacturing).

Yawei *et al.* (2017) provided a detailed review of Passive Self-Sensing Tags (PSST) that could be used to give information about the material it is placed on through the changes associated with the emitting parameter. "It can be envisioned that PSST holds potential to replace some conventional wireless sensors as a new sensor node in the IoT era. More importantly, the static and dynamic information collected by PSSTs during a products life-cycle could improve logistics management, health monitoring, maintenance, remanufacturing and process development." (Yawei *et al.*, 2017).

4 Equipment-Related Work

This section discusses emerging digital equipment, tooling and systems (not fitted to the product) found in the remanufacturing space. Synthesis has been based on Ranky (2001) who discussed the trends in disassembly (a major process steps in remanufacturing) highlighting two research streams:

1) the development of technology, methods and algorithms for web-based virtual disassembly platforms

2) smart robotic disassembly cells using intelligent sensing and real-time adaptation

These streams were adapted to summarise the findings related to “equipment”, but as remanufacturing consists of more than disassembly (All-Party Parliamentary Sustainable Resource Group, 2014) “disassembly” was replaced by “remanufacturing” in the section titles.

4.1 Technology for Web-Based Virtual Remanufacturing Platforms

The management and activity of disassembly is not unique to remanufacturing. It also supports MoL maintenance, repair and overhaul (MRO), servicing and upgrade activities along with EoL processing. It is therefore beneficial to consider disassembly planning (DP) at the product design stage. DP for remanufacturing is a popular area for VR application research, as “virtual reality implies a quality revolution in the manufacturing system and in product performance and quality” (Coates, 2000) that is most effective at the product design stage (Chang *et al.*, 2017a). The accuracy of the decisions made at the BoL for EoL processing may benefit from IoT through the feedback of information from MoL activities including usage, servicing and recovery (Brundage *et al.*, 2018).

Automated disassembly sequence planning (DSP) combined with VR is the subject of several papers including that by Siddique and Rosen (1997) who uses a vehicle console as a case study allowing designers to critique disassemblability of different models. Similarly, Zwolinski *et al.* (2007) describe the use of VR at the design stage with design-for-(dis)assembly rules to meet changing requirements. Chung and Peng (2008) describe a web-based VR environment for dynamic selective DSP using real-time resource data to calculate process parameters, whilst Mircheski and Rizov (2018) demonstrated a non-destructive planner supported by AR and RFID.

Santochi *et al.* (2002) provided a detailed critique of computer-aided disassembly software to assist DP. Modularising the software’s features, capabilities, speciality or overlap, they identified a lack of development in the areas of design for DP, subassembly detection, and systems capable of dealing with destructive disassembly. More recently, Ghandi and Masehian (2015) called for additional research focused on the (dis)assembly of flexible components, tooling and fixtures, thermal expansion, contraction and deformation in their thorough review of (dis)assembly path planning methods including VR.

More generally, Mourtzis *et al.* (2014) explored developments, applications, trends and challenges in simulation methods including VR and AR in product/process design, planning and verification. Whilst their work focused primarily on manufacturing, it does pertain to remanufacturing, particularly when it has the same goals as manufacturing in terms of flexibility, quality, velocity and cost (Ferrer *et al.*, 2011) and current methods can and should be used in remanufacturing (Ferrer and Clay Whybark, 2000). The illustration by Mourtzis *et al.* (2014) adapted to include training, captures the manufacturing, and potentially the remanufacturing business function where simulation methods and tools such as VR, AR and digital twins could be utilised (Figure 3).

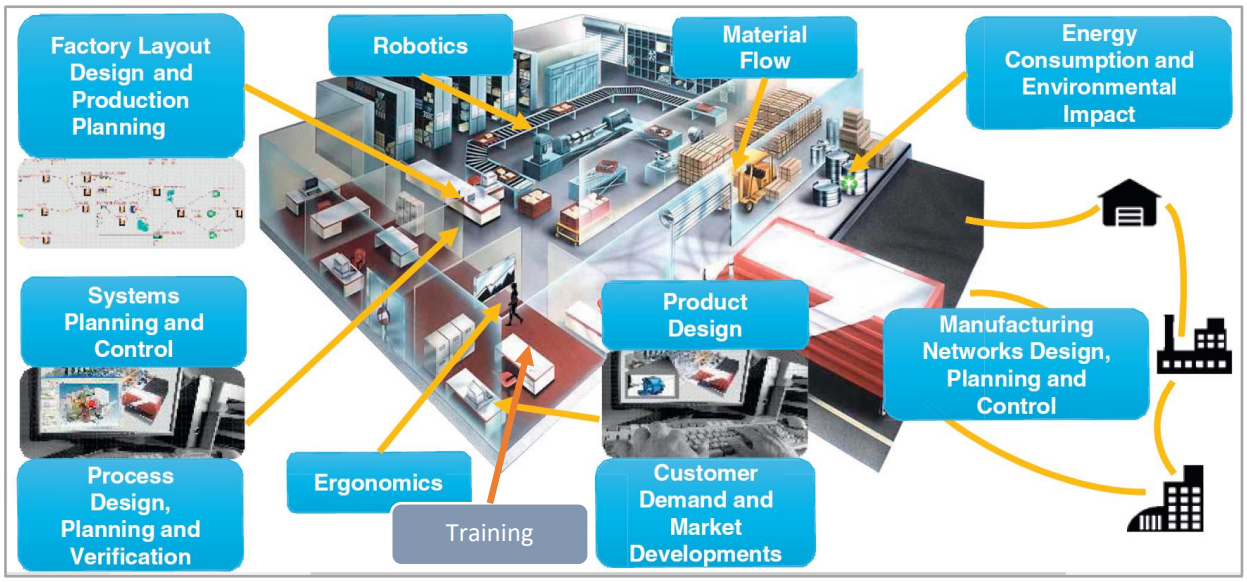


Figure 3 -Simulation in contemporary (re)manufacturing (adapted from Mourtzis et al. (2014))

Takata *et al.* (2001) used a 3D product model to provide DSP, direction and tooling information to the operator on a head-up display. The model was updated in real-time considering feedback from 6-axis sensors fitted to the operator's gloves. They identified the need to expand the algorithm for operation monitoring to recognise more generic movements, a limitation potentially alleviated by tracking the product (not the operator), as proposed in Chang *et al.* (2017) and Osti *et al.* (2017). Chang *et al.* (2017) used AR to communicate an auto-generated DS to the operator, overlaying the real environment with text and images, demonstrating the application on the disassembly of a coffeemaker (Figure 4). Similarly, Osti *et al.* (2017) demonstrated an AR system that used CAD, AR, a Leap Motion Controller device, glasses and a strategy evaluation algorithm, that permitted the visualisation of information concerning the disassembly path and tooling required to complete the task. On the other hand, Mircheski and Rizov (2017) utilised a mobile phone or tablet to present the DS information. From a technical perspective, all three papers presented simple but capable demonstrations of CPS offering a vision of future AR-supported disassembly activities.

Figure 4 -AR demonstrated in disassembly (Chang et al., 2017)

Menn *et al.* (2017) explored the use of 3D-PDF, Utility-Film (a language independent video tutorial that represents the real-world) along with illustrated manuals to train remanufacturing operators. Evaluated with respect to product assembly time, instruction creation time, ease of distribution, usability, assembly error susceptibility and changeability, interactive 3D-PDF was identified as the best solution. Following on from this, Menn *et al.* (2018) discussed a layered curriculum for special machine-tool build and repair training (potentially representative of high-value, low frequency product remanufacturing). Using AR the operator could engage with a mock AM product to establish base knowledge before progressing onto the real product using interactive 3D-PDF to assist with variety familiarity. Finally, Menn *et al.* (2018a) documented the results of a questionnaire aimed at capturing feedback from machinery Field Service Engineers after they had used interactive 3D-PDF Learnstruments (physical interactive objects that assist with knowledge transfer of functional tasks in the workplace (McFarland *et al.*, 2013)). They suggested that this method could support training. However, issues with limited portability, susceptibility to errors, and high cost of the equipment were identified as barriers to implementation.

Müller *et al.* (2016a) documented the use of a simulated teaching game to support the up-skilling of operators using VR and motion tracking technology to encourage learning in manual work environments, relevant to remanufacturing due to the high proportion of manual processing. Similarly, Müller *et al.* (2016b) presented an AR tool designed to transfer knowledge to trainee operators through the tracking of their hand movements monitoring them against a pre-defined plan using a Kinect camera. Interestingly, the results suggested paper-based training provided faster learning and fewer operational errors, but problems with the hand recognition methods and differences between the teaching/learning environments were recognised as potential error sources. However, the concept does show some promise for remanufacturing, as does the idea of using VR integrated with a portable coordinate measurement machine to drive standard measurement control for inspection activities (Segovia *et al.*, 2015). So far, there has been no clear direction or demonstration of how this could be achieved.

In a learning factory environment, Uhlemann *et al.* (2017a) compared a process digital twin (not realised, only described) with value stream mapping, evaluating the characteristics of both methods, as low, medium or high without clear criteria. This implied an over-simplification of the pre-requisites for building a digital twin and potentially over-rated the benefits. However, as VR has already been used in process planning, it may be possible to overlay real-time information to generate a process digital twin that could be used for educational or management purposes.

4.2 Methods (Systems) for Web-Based Virtual Remanufacturing Platforms

The methods identified in this review related to the layering of different technologies to support the sharing of product and process information. Research in this field was limited and disconnected but did provide a range of concepts across different remanufacturing sectors.

Automated identification and assessment of inbound core was the focus of Schlüter *et al.* (2018) who proposed a CPS inspection "Logic.Cube" containing cameras and scales, whereas Muftooh *et al.* (2018) demonstrated the feasibility of videogrammetry to generate a low-cost 3D model of an engine to determine influential parameters that may affect the remanufacturing process. Also in inspection, Stark *et al.* (2014) explored a multi-layered solution to improve success rates and increase automation in printed circuit board (PCB) MRO, overlaying CT and 3D scanning outputs to build error-free netlists for reverse engineering activities, using flying probes for continuity testing, and algorithms for component identification.

Should a robotic remanufacturing process exist, a cloud service could be used to provide 'Robot Control-as-a-Service' to realise real-time adaptive control to deal with uncertainties in EoL product states and unforeseen events (Adamson *et al.*, 2016). Similarly, adding I4.0 technology to machine tools could support the development of web-based distributed process planning in decentralised dynamic (re)manufacturing environments (Wang, 2013).

In sectors that have legislated targets e.g. ELV, where closer monitoring and reporting is required, it may be beneficial to install an IoT linked remanufacturing monitoring system with remote data accessing "designed and implemented to check whether the dismantled parts are properly recycled, and to collect recycling data… …[as] the real recycling rates are expected to be much lower than the depicted values since they are mostly based on recyclers' reports" (Yi and Park, 2015).

Wang *et al.* (2018) explored ubiquitous technologies in research including IoT, big data, RFID and cloud systems with a section specifically dedicated to remanufacturing. They suggested new opportunities existed for the remanufacturing industry through the harnessing of a product's lifecycle data to make decisions on its future.

Once data has been captured and analysed successfully, the use of digital twins for product/process optimisation (in remanufacturing or in MoL scenarios) has been proposed but has been limited in demonstration or application. Uhlemann *et al.* (2017) proposed the use of sensor-based tracking and vision systems fitted to machine tools. The sensors and vision systems capture real-time data on product manufacturing, to provide inputs to a 'process digital twin', potentially applicable to highly automated remanufacturing facilities. Abramovici *et al.* (2017) described the use of a 'product digital twin' allowing MoL reconfiguration options to be presented to the user via IoT and then realised, based on the results of virtual evaluation and personal preferences. Wang and Wang (2018) demonstrated a digital twin-based system for

the recovery/remanufacturing of WEEE, whereas Lejon and Jeppsson (2015) demonstrated the extension of a Product Lifecycle Management (PLM) system, to support product instances and provide links to a dashboard using a low-powered wireless sensor network. A combined solution for information management of both product use and development for functional products, can be achieved by integrating MoL information with the virtual representation (Lejon and Jeppsson, 2015).

With previously untapped MoL data available upstream to suppliers and designers, information that enables decision-making activities in closed-loop supply chains can also be traceable (Li *et al.*, 2015). Tao *et al.* (2016) used mobile phones as a case study to discuss the opportunities and challenges of IoT (using RFID) for lifecycle energy management, how and where the data could be used in design, production and MoL suggesting it improved EoL decision-making. Through correct management of BoL, MoL, and upgrade options data, the alignment of the real product and its digital twin allows for the management and evaluation of information and environment extending product life, turning potential EoL products back to in-life products through remanufacturing.

In order to realise these opportunities, there is a need for standardised machine readable information to link software packages to support through-life data management for "fast and error-free processing of engineering information" *(*Ivezic *et al., 2014)*. This subject was reviewed by Pagoropoulos *et al.* (2017) who detailed the use of digital technologies in the CE suggesting greater focus was required on data architecture and integration. Schmidt *et al.* (2017) discussed different data types and their availability within a manufacturing ICT system suggesting ontologies overlap which allowed for data use and knowledge share across platforms. However, they identified that links needed to be explicitly defined and whilst "data from the whole population of identical or similar components could be retrieved… …data from a population of components cannot be simply aggregate, without consideration of contextual information" (Schmidt *et al.*, 2017). This adds significant complexity to the real-time monitoring of MoL products or data collection for EoL processing. Vast quantities and variability in the quality of the data will need to be handled but traditional methods are not able to deal with the demands of big data (Tsai *et al.*, 2015). Remanufacturing could benefit from big data and its use has been proposed in several areas including:

- The optimisation of production performance of AM (Majeed *et al.*, 2018).
- The collecting of data relating to a device from BoL to EoL, monitoring the generation and trade of WEEE for the purposes of law enforcement, policy making and administration (Gu *et al.*, 2017).
- The coordination and analysis of materials information, with potential to provide EoL product knowledge (Jose and Ramakrishna, 2018).
- The tracking of changes made to products using big data methods during MoL MRO to support operations management (Roy *et al.*, 2016).

- To drive decisions in the supply chain (Nguyen *et al.*, 2017, Viet *et al.*, 2018), cleaner production to improve competitive advantages (Zhang *et al.*, 2017a), or PLM (Zhang *et al.*, 2017).
- Dynamically mapping relationships between disassembly attributes and industrial robot's (IR's) real-time data using a meta-data model of IR, the data source and classification of the disassembly process, and the in-cycle data which is mined and analysed using the Bees Algorithm (Zheng *et al.*, 2017).

The diversity of the applications for big data in remanufacturing can be seen above but gaps exist, and an end-to-end view is yet to be presented. Friedemann *et al.* (2016) identified two key publications related to standardisation in I4.0 including 'Reference Architecture Model Industrie 4.0' and the 'Industrial Internet Reference Architecture'. However, solutions need to be found in the compatibility of definitions for remanufacturing along the entire value chain, information security and confidentiality, safe sharing of sensitive data between stakeholders, and the establishment of stable interfaces for transactions and communications to occur (Jensen and Remmen, 2017). Other concerns include security, accuracy of sensors, standardisation of devices and the energy use associated with IoT technology, efficient naming and identity management, scalability, and the need for more "high-powered information collection, advanced data processing algorithms, and information gathering platforms" *(Tao et al., 2016)*.

4.3 Algorithms for Web-Based Virtual Remanufacturing Platforms

Algorithms have been incorporated into some of the systems already discussed to assist in the identification of components (Stark *et al.*, 2014) and motions (Takata *et al.*, 2001), or for DSP (Osti *et al.*, 2017). More specifically to remanufacturing, Hao *et al.* (2018) discussed a hybrid process planning algorithm to determine a reasonable machining route for both CNC machining and AM for product remanufacturing using CAD. Additionally, Zhou *et al.* (2018) presented a solution to generate a service Bill of Materials (sBoM), that could also be applied to remanufacturing as an EoL BoM. The sBoM would be created from a general product structure BoM via a conversion tool (processing data potentially from IoT sources) demonstrating significant improvements in sBoM accuracy, and a reduction in lead-time and labour requirements. In a different application aimed at identifying the most suitable EoL products for remanufacture, Meng *et al.* (2016) described a decision-making tool that used a hybrid of calculations including cost-benefit analysis and a fuzzy inference model (EoL product quality based on use, performance and reliability), that estimated recovery value and cost. Combined with qualitative factors including technology compatibility, market performance, environmental impact and consumer opinion, the results were ranked and were found to be superior to those obtained using other methods.

Interestingly, however, Craig (2017) highlighted the risks posed to the increasing reliance on complex algorithms working with digital technologies, warning the greater the complexity, the less transparent the algorithm became, making systems vulnerable to (un)intentional biases with potentially catastrophic business

consequences. As an alternative to using algorithms to interrogate raw data, Zhang *et al.* (2018) presented a solution that took images of waveforms and evaluated the pixels, just as humans would look for trends in graphs, for automatic identification and classification of machine conditions.

4.4 Smart Robotic Remanufacturing Cells using Intelligent Sensing and Real-Time Adaptation

The only paper that successfully demonstrated a robotic remanufacturing solution referencing IoT, I4.0, AR or VR was that by Ruggeri *et al.* (2017). Mentioning I4.0 briefly as a key research trend in human-robot collaboration, they presented a reconfigurable semi-collaborative cell using the ABB YuMi robot for PCB remanufacturing. They raised interesting issues specific to micro component handling that affected gripper design, precision of robot movement and vision system resolution. The latter two issues were also recognised by Stark *et al.* (2014) as they discussed similar micro-scale environments. The 'training' of a robot using a vision system to track human movements and tooling to repeat the disassembly of a TV was discussed by Vongbunyong *et al.* (2017) but was not realised, possibly due to the large positioning errors inherent in the proposed system.

Whilst there appeared to be a lack of smart robotic remanufacturing demonstrations, there is still an expectation that they will be utilised in the remanufacturing factories of the future (Agency for Science, 2016) suggesting more research is needed to realise it. Additionally, as full automation of the EoL disassembly process is unlikely due to variations in core quality and quantity etc., partial automation using collaborative robots, or robots in a collaborative way, may offer a solution (Chen *et al.*, 2014, Wegener *et al.*, 2014, Wegener *et al.*, 2015). Faber *et al.* (2015) discussed collaborative working from an ergonomics perspective suggesting older operators could be supported by robots, a belief shared by the Society of Motor Manufacturers and Traders (SMMT, 2017), and Li *et al.* (2018) who provided an extensive review of robots and automation in disassembly.

Bogue (2017) reviewed current standards and their fit to the emerging collaborative robot offering, focusing on ISO/TS15066:2016 (International Organization for Standardization, 2016) before providing an interesting insight into their use outside of the guarded factory environment (more reflective of a collaborative remanufacturing factory), and the different solutions manufacturers have used to meet the standards. Marvel and Norcross (2017) critically analysed ISO/TS15066:2016, specifically the scenarios where the minimum protective distances between robot and operator in the collaborative workspace, below which a safety-rated, controlled stop is triggered highlighting the instances where the assumptions may not be sufficient to protect the operator, or where a stop would be triggered by a scenario that is not dangerous. Han *et al.* (2018) looked to improve response times of collision detection and real-time path re-planning for robot arms using a human arm (modelled as cylinders) as dynamic obstacles. Meziane *et al.* (2017) described the creation and linking of

a grid, waypoints and smoothing polynomials for the trajectory planning of robot motion in order to avoid moving objects and jolting of the arm.

5 Process-Related Work

This section considers the remanufacturing business process with respect to its key interfaces (customers and suppliers). The evolution of I4.0 technology has opened up several parallel process improvement opportunities, including real-time monitoring and allocation of resources, EoL and MoL decision-making. Potential applications expand beyond remanufacturing to MoL MRO strategies. The link between remanufacturing and MRO should not be ignored with many articles discussing the benefits of monitoring products at the MoL stage. This relationship will be further explored along with real-time monitoring and the potential to improve core visibility.

5.1 Remanufacturing for Maintenance

Predictive maintenance is one of the leading use cases for IoT and I4.0 (Madslien, 2018) and with the process of maintenance acting as both supplier, through the provision of cores, and customer, as a user of remanufactured products, there is a need to reflect on the interconnected relationships between them in this new digital age.

The purpose of a product from a lifecycle management perspective is to meet user requirements, minimise environmental impact and in some instances maximise profit, each influenced by customer demand and product condition, deterioration or failure (Takata *et al.*, 2004). It is necessary to recognise the "optimisation of a product's life cycle is a strategic objective of development for industrial manufacturing" (Westkämper, 2003). Gao and Wang (2017) discussed sustainable research practices in machine tool MRO, suggesting repair and retrofitting is more common than remanufacturing in this high value sector. Remanufacturing is only likely when the product no longer meets the expectations of its user, or when there is no better alternative or cost-effective product available.

Franciosi *et al.* (2017) discussed the development of a model to support decision-making through the evaluation of different maintenance options for the replacement of failed parts with either new, reconditioned, remanufactured or used spares to promote more sustainable practice. The authors identified I4.0 technology as a tool that could improve the availability of component data. They considered using a decision-making tool only after a component had failed. However, their tool has the potential to support MoL opportunities associated with improved maintenance. These aspects were thoroughly explored by Roy *et al.* (2016), considering the assessment of product health and degradation information through IoT and I4.0 to support continuous maintenance for product improvement and life extension. Similar reviews of techniques designed to assist in extending life, analytical methods for estimating recoverability and remaining machine

life (Gao *et al.*, 2018) and the implementation of prognosis and health monitoring of machines in the smart factory (Gil-Yong *et al.*, 2018), appear to align with the opinions of Ondemir and Gupta (2014). The latter authors have suggested that correct application of this monitoring and prognosis offers a solution to a significant remanufacturing planning problem, the management of uncertainties in the condition of EoL products, and the impacts of these on recovery operations and profit.

Also considering high value assets like machine tools, Westkämper (2003) discussed assembly and disassembly from a lifecycle perspective and the networking of assets for service provisioning, calling for the consideration of parallel progression. He highlighted that during the lifetime of a manufacturing centre, technologies, capabilities and efficiencies of new products will evolve and it is the difference between the two entities that affect consumption and life-expectancy. Similarly, Xiao *et al.* (2018) explored the LCA of heavy-duty off-road (HDOR) vehicles remanufactured in different locations and compared them against that for a newly manufactured product to evaluate the resulting revenue and environmental impact. Considering production volumes and life distribution expectations, they estimated the peak in the EoL of a specific product to support remanufacturing process planning.

5.2 Remanufacturing and Real-Time Monitoring

Ondemir and Gupta (2014) provided a detailed insight into 'remaining useful life' as an indicator of product quality to feed into decision-making tools that optimised disassembly costs and process planning. Describing an interesting integrated system using RFID and embedded sensors to provide BoL and MoL data to EoL processing systems, they identified the serial numbers of the products to be remanufactured, and the recovery options available based on the perceived product quality.

Adding I4.0 technology to products for MoL monitoring and real-time management has been demonstrated with the possibility to develop holistic self-management systems Ivezic *et al.* (2014). Whilst it could become economically viable for complex high-value products (like HDOR parts that are important, competitive and very dynamic in European remanufacturing (Saidani *et al.*, 2017)) to contain smart DCD, it makes little economic sense to add them to low-value products as the variety, volume and velocity of data, its security, the efficiency of processing, along with conflicting requirements of stakeholders, add complexity and cost to its implementation (Gu *et al.*, 2017). Instead, there is a need to develop processes and systems for efficient and effective disassembly and recycling, or hybrid technical concepts that integrate e-services (Westkämper, 2003) for low value and medium value products, respectively.

5.3 Remanufacturing Core Supply

For remanufacturing to be economically feasible, there must first be availability of core and a demand for remanufactured products, with the acquisition of EoL products being the first step in the remanufacturing system (Jiaping *et al.*, 2015).

As IoT has the potential to digitally link the supplier and customer (Man and Strandhagen, 2017), it may assist in the procurement of used products (Abubaker *et al.*, 2017) supporting remanufacturing core acquisition. Vikas *et al.* (2016) summarised the diversity in reverse supply chains, highlighting the need to better understand characteristics to optimise customer satisfaction and to best utilise resources. They stated that the "management of returned items is now perceived as an opportunity to improve customer service perceptions and loyalty" (Vikas *et al.*, 2016).

Ruggeri *et al.* (2017) considered the remanufacturing potential of PCBs, and mobile phones were used as examples in five articles suggesting there is a vision to consider the remanufacturing of consumer electronics. With more than 1.5M smart phones sold in 2017 (Statista, 2018) there is growing recognition that low-value, high-volume core can be valuable when reclaimed en masse. To exploit this opportunity, Apple Inc. presented "Daisy" in 2018, an automated cell capable of dismantling two-hundred iPhones/hour (Apple Inc., 2018). Currently designed to dismantle iPhones for recycling, the same facility could potentially be used to disassemble them for core reclamation and remanufacturing. Disassembly is a key activity in remanufacturing that is more challenging to automate than assembly due to EoL product variability (Vongbunyong et al., 2017).

Visibility of potential core is key to business planning and as already identified it can be facilitated by DCD and real-time monitoring. The increase in connectivity achievable with IoT devices, combined with the development of core finding web-based systems could transform the remanufacturing industry. Ryen *et al.* (2017) discussed the application of a nature inspired foraging model for WEEE core sourcing using an 'E-waste forager', translating ecological model parameters and animal behaviours into e-waste equivalents. They proposed the imitation of nature to "develop the partnerships, infrastructure, tools, and policies needed to ensure a long lasting, adaptable, and profitable e-waste ecosystem that can endure material scarcity, price fluctuations, or innovation changes" (Ryen *et al.*, 2017).

6 Organisation-Related Work

The move in manufacturing towards more sustainable methods and the parallel emergence of I4.0 necessitate changes in business strategies and management styles. Sustainability in companies can be supported through the integration of management systems, with a combination of bottom-up and top-down approaches being most effective (Lukman *et al.*, 2016).

Should a business translate towards providing services as well as products as part of a Product-Service-System (PSS), the organisational structure will need to be modified to cope with the new challenges (Stark *et al.*, 2014) and, as the remanufacturing industry can provide significant support functions to PSS organisations, they will have to adapt accordingly. This will force remanufacturing firms to invest in more sophisticated ICT to take

advantage of BoL and MoL data for EoL processing, and to regulate sustainability consciousness to meet changing customer and corporate environmental expectations.

6.1 Business Models

According to Lazarevic and Valve (2017) in their article that discussed expectations towards the CE transition, digital enabling technologies were key to enhancing real-time information exchange amongst users which could facilitate business models for repair and reuse. Additionally, there is general agreement that the success of a CE depends on new business models that extract the value that is still embedded in EoL product (Esmaeilian et al. 2016). The business models that best reflect CE principles provide services or solutions that are of high quality, have technology cycles that are longer than their life expectancy, and offer both short-lived and durable products with restoration methods available (Yeo et al. 2017). Interestingly the sectors that currently utilise this type of model are often influenced by local or regional regulations.

At industry sector level, there are many national and international regulations that align to the principles set out by the United Nations Sustainability Development Goals (United Nations, no date). Examples include the European Parliament and European Council's ELV directive 2000/53/EC, and Waste Electronic and Electrical Equipment (WEEE) directive 2012/19/EU, aimed at reducing waste and hazardous material to landfill (European Council, 2000, European Union, 2012). Hughes (2017) summarised the work of the EU regarding standards and legislation focusing on the effects of the 2015 CE Package that is due to develop generic standards for eco-design requirements in 2019. Covering parameters and methods to assess remanufacturability, component access to facilitate remanufacturing, evaluation indexes or criteria, identification and relevant documentation, Hughes (2017) provided an insight into impending standards before questioning how the EU could ensure that the "revolution expected to be brought about by both the 'Internet of Things' and 'Industry 4.0' deliver[s] the European Commission's goal of creating a circular economy" (Hughes, 2017).

There were also examples of industries that employ remanufacturing practices but self-regulate, that could benefit from I4.0 technology. Comparing the regulated automotive industry and the EoL directive, with the self-regulated shipping and aircraft industries, Jensen and Remmen (2017) highlighted the high recycling rates, low material to landfill, and the different markets for reuse, as well as recognising the need for an information management system to handle data transferred through the entire product lifecycle, from all three industries. As I4.0 digitally connects the customer with the supply chain (Man and Strandhagen, 2017) it may eventually serve both regulated and self-regulated businesses. Similarly Saidani *et al.* (2017) discussed best practices and challenges comparing the HDOR vehicle industry (that is not directly legislated) with the automotive sector suggesting that embedded telematics (automotive systems that support roadside and remote diagnostics) could provide useful information for life extension and EoL decision-making.

There were various products, processes and strategies used for remanufacturing that were presented by Tolio *et al.* (2017) in their thorough review of smart enabling technologies in design, management and control using examples from well-known OEM's. Proposing a new manufacturer-centric CE model and touching on the requirements to meet it, they suggested that a higher technology readiness level needed to be achieved, particularly in the areas of integration and demonstration to support the transition to I4.0. These areas are being pursued by a number of manufacturing research collaborations as reported by Bueno *et al.* (2017) who summarised the work across Europe, discussing existing government backed, public and private programmes, plans and roadmaps covering initiatives such as "Manufuture" and "Factories of the Future".

6.2 Expected Growth of ICT

Data sharing along a product's life from concept visualisation to EoL processing has already been discussed. However, to realise sustainable benefits from I4.0 including value co-creation, closer links to stakeholders, complex decision-making (through AI and machine learning), and the expansion of PSS, it is necessary to expand remanufacturing ICT capabilities. The "ICT support sector is able to support the CE, by offering existing services in new ways, or developing entirely new services, to enable their customers to decouple profits from resource consumption" (Heyes *et al.*, 2018).

Developments in emerging technologies and CPS require exponential growth in the ICT infrastructure (Raihanian Mashhadi and Behdad, 2018), so too does the need to harness the knowledge of engineers in increasingly complex manufacturing scenarios to support the evaluation of different processing options by provisioning the relevant information to the experts at the right time (Belkadi *et al.*, 2015). Taken from Wang (2014), Figure 5 illustrates the data management for WEEE through its entire lifecycle using cloud storage with a more detailed discussion and IoT application found in (Wang and Wang, 2017). This vision could also be applicable to non-WEEE products, cycling the information from OEM, to distributor, to user, and back to the OEM.

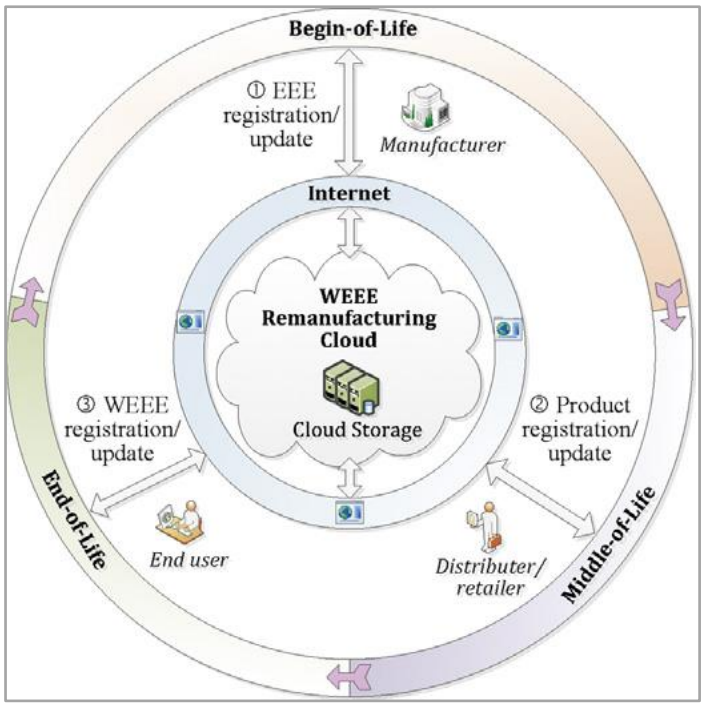


Figure 5 –Cloud-based WEEE data management for remanufacturing (Wang et al., 2014)

The growth requirement of the ICT provision varies depending on existing ICT infrastructure, business model, company and expectations, but opportunities exist to harness the scalability of cloud-based manufacturing systems. It can increase sustainability by supporting collaborative design, greater automation, improve resilience and enhance EoL processes (Fisher *et al.*, 2018).

Romero and Vernadat (2016) delved into the specifics of enterprise information systems (EIS), reviewing their history and future. They claimed that continued growth in cloud-based EIS could change the way businesses purchase, use and structure their ICT, allowing for highly integrated networking of industries at different levels. Jensen and Remmen (2017) suggested that integrating information in an EIS could reduce business risk through increasing product understanding. However, they also raised concerns over data management and compatibility of definitions between the stakeholders and the challenge that this posed when implementing an EIS, particularly in product stewardship business models.

Focused specifically on the standards associated with information systems for closed-loop lifecycle management using IoT, Kiritsis (2011) discussed the specifications related to data type and format, reporting on systems that offered some level of capability in this field. Aiming for seamless and transparent interoperability, they used a read-write capable RFID transmitter and receiver, linked with sensor feedback to an internet-based system, on an EoL vehicle with OEM information to make decisions on the recovery of components.

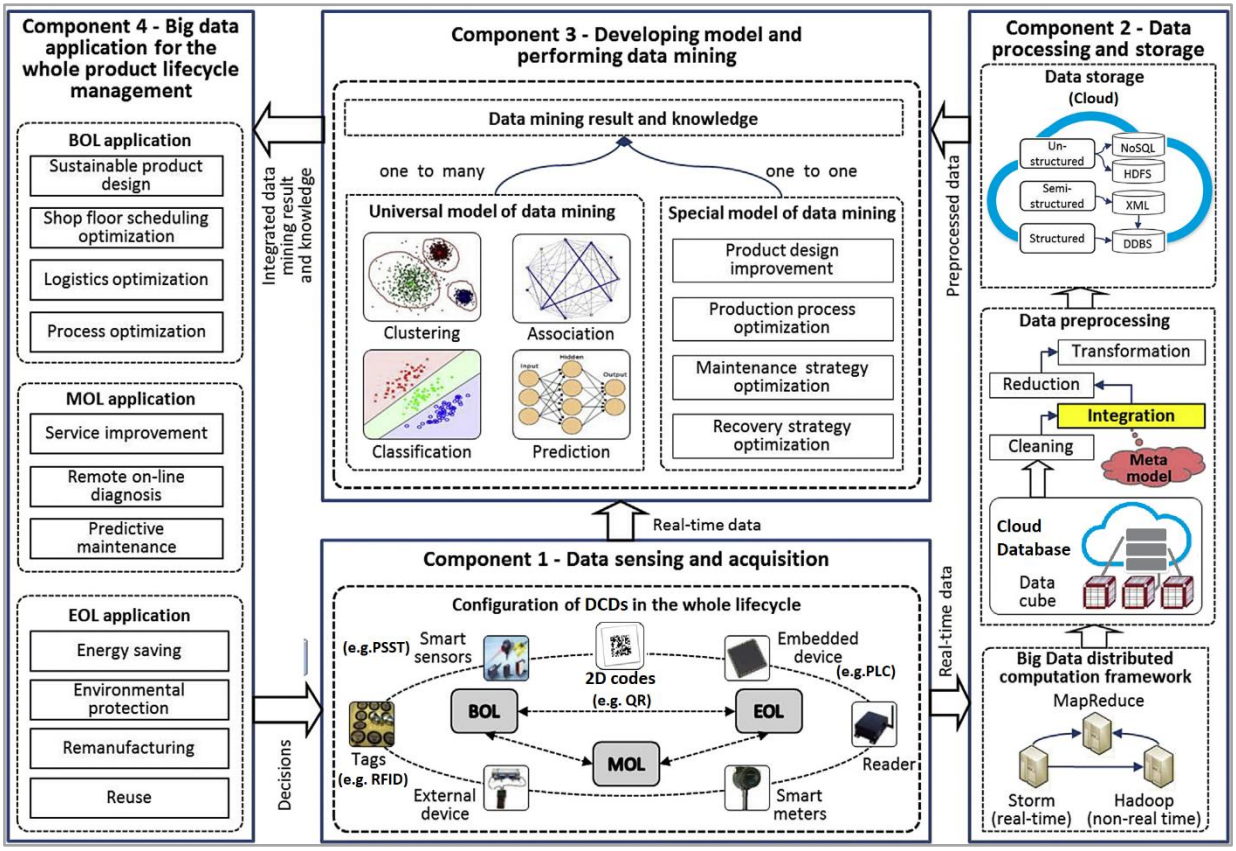


Figure 6 –ICT infrastructure to organise data-driven products for lifecycle management (adapted from Zhang et al. (2017))

The most complete example of the ICT infrastructure required to organise data-driven products for lifecycle management (Figure 6) was adapted from (Zhang *et al.*, 2017) by adding 2D codes and cloud databases as these have been identified in this study as providing value to remanufacturing. Starting at "Component 1" DCD, along with embedded and external devices, are used at BoL, MoL and EoL to support design, scheduling, optimisation, diagnostics and remanufacturing (Component 4). Components 2 and 3 represent data cleansing, reduction and post-processing before it is made available for mining to support decision-making.

6.3 Sustainability Consciousness

The cost of waste to the environment, the depletion of natural resources increasing commodity costs, improvements in technology and changes in consumer demands are building momentum in the support of a CE of which remanufacturing is a key strategy to increase efficient use of resources (Preston, 2012).

In September 2015, world leaders set out a declaration of commitment to 'Sustainable Development Goals' with the aim of balancing the economic, social and environmental needs of the planet by 2030 (UN General Assembly, 2015). The activity of remanufacturing links to two of the targets (9.4 and 12.5) supporting the international community's vision of increasing sustainability through cleaner technologies, processes and manufacturing strategies and reducing waste. It is no surprise then that sustainable development is a popular topic for researchers with enthusiasm and belief that I4.0 and remanufacturing can support it.

However, the remanufacturing business itself should also promote sustainable business practices. To lead the transition towards more sustainable businesses, Carvalho *et al.* (2018) identified two emerging types of entrepreneurs, the "ecopreneur" and the "sustainable entrepreneur". These have different objectives and approaches to building sustainable industry, but both represent new roles and environmentally conscious leadership styles in the I4.0 manufacturing future.

7 Discussion, Conclusions and Further Work

This article has reviewed published work on Industry 4.0 (or smart manufacturing) technologies, in particular, the Internet of Things, Virtual Reality and Augmented Reality and their use in remanufacturing. It can be used by researchers in the field or remanufacturing to quickly locate relevant material and open research topics. Trends and gaps have been discussed, summarised according to four value-creation factors, Product, Equipment, Process and Organisation, and presented in Figure 7.

Primarily used to repair EoL products, AM systems integrated with the IoT have possibilities, but realisation has not been demonstrated and concerns exist over the current trajectory of developments in this field to support sustainable practices.

The focus of most of the papers on DCD to support remanufacturing was on the addition of 2D codes or RFID devices to carry data. Additionally, instead of relying on capturing data throughout a product's life, it may be possible to develop sensors that only send information on a change of state, i.e. when a particular measurable failure occurs. With the DCD fitted to a component in a permanent, semi-permanent or temporary application to meet the needs to track, trace or transfer limited amounts of data over short distances, it can also be retrofitted to products already in-use. For complex products finding a location for the 2D/QR code that can be line-of-sight readable can be difficult, with component properties affecting signal strength and transmitter-responder capabilities.

Figure 7 - Research trends and gaps in I4.0 technologies for remanufacturing

Both low and high value products need to be considered by remanufacturers to support the move towards a CE, but each requires a different, perhaps a matrix style, approach to the processes used. Most of the findings relating to "process" considered high-value assets that form part of a larger system requiring maintenance and servicing, utilising MoL data to support decision-making. In this scenario, it is key that the remanufacturers work closely with the maintenance functions to exchange cores for remanufactured parts, with the potential to provide availability forecasting that can support procurement strategies.

Should MoL data be available, it may assist with failure diagnostics and decisions on repair or replacement (with new, remanufactured or spare) products. In this sector, it is necessary to consider the impact of the remaining life of the host product, the increase and unpredictable failure modes expected with age, the impact of extending product life and the decrease in spare part availability, production data and potential loss of the OEM (Stark *et al.*, 2014) due to their long MoL phases. Providing relevant and timely MoL data to the people or intelligent systems that require it to support core management is key, but it is necessary first to understand the potentially conflicting data requirements of the stakeholders.

Almost 20 years ago, Coates (2000) recognised the potential for digital technologies to revolutionise manufacturing. The networking of equipment in industry is not new there are opportunities to utilise I4.0 concepts to enhance existing equipment transforming it into smart manufacturing systems (Jin *et al.*, 2017) but this has hardly been demonstrated in remanufacturing.

VR is already used in industry and is being developed to enhance product and process design, optimisation and verification. AR, however, remains mainly in the academic domain, with questionable value in industry. It has been proposed for training but there were few real-world examples and little evidence to support it as a significant business need. There have been discussions over its use in customer visualisation and customisation (including in textiles remanufacturing (Larsson, 2018)) which may offer some benefits from a socio-economic perspective (Fox, 2016) but its remanufacturing specific application remains unclear. There is a need to further explore the benefits that could be realised using digital twins. 'Product twins' may provide MoL data that could influence EoL activities and 'process twins' could assist in facility design and management should the remanufacturing industry increase its automation capability.

There is sufficient research being conducted on robots in remanufacturing to justify a stand-alone review. Robotics and flexible remanufacturing systems (including real-time adaption) are key to dealing with the variability in demand, product generation, core quantity and quality but their integration into an I4.0 remanufacturing environment is still relatively unexplored.

There are opportunities to apply intelligent algorithms to solve complex remanufacturing problems. Some have already been demonstrated in product selection optimisation and DSP. However, their integration into

automated remanufacturing solutions is yet to be fully demonstrated which is key to evaluating capabilities and sharing concepts with technology development partners. Remanufacturing equipment and its monitoring as well as the allocation of processes to assets using the IoT and web-based decision-making algorithms, are likely to operate in a similar way to manufacturing so it would be prudent to remain engaged with those leading this field to understand the infrastructure necessary to achieve such integration.

For remanufacturing businesses to prosper in this new era of connectivity, they will need to invest in ICT and associated support staff that will change the organisation. With the ability to identify, locate, track and interact with products remotely, it is possible to extract more value from remanufactured products, enabling different collaborative business opportunities and solutions (Marconi *et al.*, 2018) that are particularly suited to flexible, highly reactive SMEs (Romero and Noran, 2017). For OEMs who remanufacture their own products, the new structures will need to challenge the long approval cycles to realise the possible technology revolution for remanufacturing (Yeo et al. 2017). As for independent remanufacturing businesses, they will need to develop closer connections with their supply chain utilising ICT to close the gap between their suppliers and customers. Scalable, on-demand cloud systems have the potential to support remanufacturing businesses that experience peak-and-trough demand cycles associated with the lifecycle of the host products. The quality of service from ICT including bandwidth, performance and security remains a concern, but this is not unique to I4.0 and applies to all IoT applications.

Future remanufacturing businesses ought to consider sustainable practices with CE in mind during I4.0 planning and implementing. The expected continued increase in raw material costs will encourage both regulated and non-regulated industries to consider CE principles including remanufacturing and there may well be a shift towards PSS models that remanufacturing will have to support.

Returning to the value creation factors, further research topics are presented in Figure 8. The factor requiring the greatest focus is 'Equipment' due to its vastness, with a significant need to develop and demonstrate the concepts discussed.

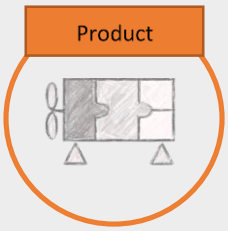
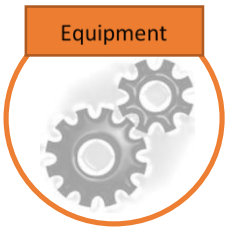
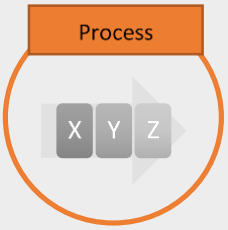
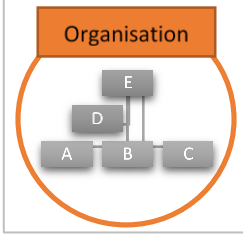
Value Creation Factor	*To exploit emerging digital technology in remanufacturing there is a requirement to:*
	➢ define the information needed at EoL that can be stored on the product at BoL ➢ consider the opportunities of embedded or external DCD ➢ explore the existence of other data storage and transfer devices that could be used ➢ clarify what information DCD should carry in addition to their unique ID ➢ explore the consequences of AM products ➢ define the benefits of combining AM with IoT ➢ align the AM trajectory to support sustainability
	➢ demonstrate AM linked to IoT ➢ develop VR solutions to assist DP, subassembly detection, and destructive disassembly ➢ develop VR solutions to explore disassembly of flexible components, tooling, fixturing, component thermal expansion, contraction and deformation ➢ demonstrate AR using real problems to clarify business need and benefits ➢ explore opportunities to use digital twins for product or process optimisation ➢ demonstrate I4.0 concepts to enhance existing shop-floor equipment transforming them into smart systems ➢ explore reconfigurable systems integrated with IoT ➢ develop specific information collection, advanced data processing algorithms, and information gathering platforms ➢ evaluate the establishment of an EoL database containing reverse logistics information using IoT ➢ expand the research into the use of robots ➢ explore the attributes of collaborative robots for specific activities ➢ demonstrate the application of AI to solve complex problems like robotic DP
	➢ consider the different requirements of low-value, high volume/high-value, low volume products and how this affects the utilisation of IoT ➢ explore how to structure a real-time data-driven optimisation method for production scheduling ➢ define the information required at EoL that can be stored on the product in MoL ➢ explore the automatic identification and capturing of MoL data from the product ➢ evaluate the demand from industry to have BoL and MoL for EoL processing ➢ develop tools and evaluate the use of IoT to estimate and manage remaining life
	➢ explore how I4.0 can support the industry in employing sustainable practices ➢ develop measurements to enable tracking of businesses towards sustainability using I4.0 ➢ explore changes in organisation from linearly connected to networked stakeholders and the new information streams that may be generated ➢ explore the applicability of machine learning and AI in decision-making at management and operations level

Figure 8 -Further research topics categorised by Value Creation Factor

In conclusion, greater automation is required in the currently highly manual remanufacturing processes to enable the utilisation of I4.0 concepts. This will require significant investment in equipment and infrastructure, and the up-skilling of personnel to become competent at interacting with CPS on the IoT. Complete lifecycle data will need to be better understood and remanufacturing processes will need to be modified to utilise it.

The IoT will continue to expand with increasing connectivity between AR, VR and shop-floor CPS linked to process and resource control systems, and I4.0 will be realised, taking the remanufacturing industry into the digital age.

FUNDING

This research was supported by the Engineering and Physical Sciences Research Council (EPSRC) No. EP/N018524/1. We would also like to express our gratitude to the EPSRC and the Manufacturing Technology Centre, Coventry, for funding the associated studentship.

REFERENCES

Abramovici, M., J. C. Göbel and P. Savarino (2017). "Reconfiguration of smart products during their use phase based on virtual product twins." CIRP Annals **66**(1): 165-168.

Abubaker, H., D. Arthur, K. Anshuman and L. Huei (2017). "Examining potential benefits and challenges associated with the Internet of Things integration in supply chains." Journal of Manufacturing Technology Management **28**(8): 1055-1085.

Adamson, G., M. Holm, P. Moore and L. Wang (2016). "A Cloud Service Control Approach for Distributed and Adaptive Equipment Control in Cloud Environments." Procedia CIRP **41**: 644-649.

Agency for Science, T. a. R. A. S. (2016, 24 August 2016). "A new class of collaborative robots may be the future of industrial remanufacturing." Retrieved 06/09/2018, from https://phys.org/news/2016-08-class-collaborative-robots-future-industrial.html.

Alcácer, V. and V. Cruz-Machado (2019). "Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems." Engineering Science and Technology, an International Journal.

All-Party Parliamentary Sustainable Resource Group. (2014). "Remanufacturing - Towards a Resource Efficient Economy." Retrieved 06/09/2018, from https://www.policyconnect.org.uk/apsrg/sites/site_apsrg/files/apsrg_-_remanufacturing_report.pdf.

Apple Inc. (2018). New Robot, Daisy, Disassembles iPhone to Reclaim Precious Materials

Belkadi, F., A. Bernard and F. Laroche (2015). "Knowledge Based and PLM Facilities for Sustainability Perspective in Manufacturing: A Global Approach." Procedia CIRP **29**: 203-208.

Bogue, R. (2017). "Robots that interact with humans: a review of safety technologies and standards." Industrial Robot: An International Journal **44**(4): 395-400.

British Standards Institution (2010). BS 8887-220-2010 Design for Manufacture, Assembly, Disassembly and End-of-Life Processing (MADE).

Brundage, M. P., W. Z. Bernstein, S. Hoffenson, Q. Chang, H. Nishi, T. Kliks and K. C. Morris (2018). "Analyzing environmental sustainability methods for use earlier in the product lifecycle." Journal of Cleaner Production **187**: 877-892.

Bueno, R., F. Girot and M. E. Gutiérrez-Orrantia (2017). "An overview on European Manufacturing research visions and roadmaps as an answer to economical and societal challenges and opportunities." Procedia Manufacturing **13**: 1455-1462.

Butzer, S. and S. Schötz (2016). D3.3 – D3.4 Map of Remanufacturing Processes Landscape, European Remanufacturing Network.

Carvalho, N., O. Chaim, E. Cazarini and M. Gerolamo (2018). "Manufacturing in the fourth industrial revolution: A positive prospect in Sustainable Manufacturing." Procedia Manufacturing **21**: 671-678.

Chang, M. M. L., S. K. Ong and A. Y. C. Nee (2017). "AR-guided Product Disassembly for Maintenance and Remanufacturing." Procedia CIRP **61**: 299-304.

Chang, M. M. L., S. K. Ong and A. Y. C. Nee (2017a). "Approaches and Challenges in Product Disassembly Planning for Sustainability." Procedia CIRP **60**: 506-511.

Chen, W. H., K. Wegener and F. Dietrich (2014). A Robot Assistant for Unscrewing in Hybrid Human-Robot Disassembly. International Conference on Robotics and Biomimetics, Bali, Indonesia.

Chung, C. and Q. Peng (2008). "Enabled dynamic tasks planning in Web-based virtual manufacturing environments." Computers in Industry **59**(1): 82-95.

Coates, J. F. (2000). "Manufacturing in the 21st Century." International Journal of Manufacturing Technology and Management **1**(1): 42-59.

Craig, H. (2017). "Leadership and strategy in the news." Strategy & Leadership **45**(6): 58-63.

de Sousa Jabbour, A. B. L., C. J. C. Jabbour, C. Foropon and M. Godinho Filho (2018). "When titans meet – Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors." Technological Forecasting and Social Change **132**: 18-25.

Despeisse, M., M. Baumers, P. Brown, F. Charnley, S. J. Ford, A. Garmulewicz, S. Knowles, T. H. W. Minshall, L. Mortara, F. P. Reed-Tsochas and J. Rowley (2017). "Unlocking value for a circular economy through 3D printing: A research agenda." Technological Forecasting and Social Change **115**: 75-84.

Dulman, M. T. and S. M. Gupta (2018). "Maintenance and remanufacturing strategy: using sensors to predict the status of wind turbines." Journal of Remanufacturing **8**(3): 131-152.

European Council (2000). Directive 2000/53/EC of the European Parliament and of the Council on End-of-Life Vehicles, Official Journal of the European Union.

European Union (2012). Directive 2012/19/EU of the European Parliament and of the Council on Waste Electrical and Electronic Equipment (WEEE), Official Journal of the European Union.

Faber, M., J. Bützler and C. M. Schlick (2015). "Human-robot Cooperation in Future Production Systems: Analysis of Requirements for Designing an Ergonomic Work System." Procedia Manufacturing **3**: 510-517.

Ferrer, G. and D. Clay Whybark (2000). "From garbage to goods: Successful remanufacturing systems and skills." Business Horizons **43**(6): 55-64.

Ferrer, G., S. K. Heath and N. Dew (2011). "An RFID application in large job shop remanufacturing operations." International Journal of Production Economics **133**(2): 612-621.

Field, J., L. Victorino, R. Buell, M. Dixon, G. S. Meyer, L. Menor, M. Pullman, A. Roth, E. Secchi and J. Zhang (2018). "Service operations: what's next?" Journal of Service Management **29**(1): 55-97.

Fisher, O., N. Watson, L. Porcu, D. Bacon, M. Rigley and R. L. Gomes (2018). "Cloud manufacturing as a sustainable process manufacturing route." Journal of Manufacturing Systems **47**: 53-68.

Fox, S. (2016). "Open prosperity: How latent realities arising from virtual-social-physical convergence (VSP) increase opportunities for global prosperity." Technology in Society **44**: 92-103.

Franciosi, C., A. Lambiase and S. Miranda (2017). "Sustainable Maintenance: a Periodic Preventive Maintenance Model with Sustainable Spare Parts Management." IFAC-PapersOnLine **50**(1): 13692-13697.

Friedemann, M., T. U. Trapp, J. Stoldt, T. Langer and M. Putz (2016). "A Framework for Information-driven Manufacturing." Procedia CIRP **57**: 38-43.

Gao, R. X. and P. Wang (2017). "Through Life Analysis for Machine Tools: From Design to Remanufacture." Procedia CIRP **59**: 2-7.

Gao, W. J., B. Xing and T. Marwala (2013). Teaching - Learning-based optimization approach for enhancing remanufacturability pre-evaluation system's reliability. Proceedings of the 2013 IEEE Symposium on Swarm Intelligence, SIS 2013 - 2013 IEEE Symposium Series on Computational Intelligence, SSCI 2013.

Gao, Y., D. Chang, T. Fang and T. Luo (2018). "The Correlation between Logistics Industry and Other Industries: An Evaluation of the Empirical Evidence from China." The Asian Journal of Shipping and Logistics **34**(1): 27-32.

Ghandi, S. and E. Masehian (2015). "Review and taxonomies of assembly and disassembly path planning problems and approaches." Computer-Aided Design **67-68**: 58-86.

Gil-Yong, L., M. Kim, Q. Ying-Jun, K. Min-Sik, T. J. Young Kim, Y. Hae-Sung, M. Sangkee, K. Dong-Hyeon, M. Jeong-Wook, O. Jin Woo, C. In Gyu, K. Chung-Soo, W.-S. Chu, J. Yang, B. Bhandari, L. Choon-Man, I. Jeong-Beom and S.-H. Ahn (2018). "Machine health management in smart factory: A review." Journal of Mechanical Science and Technology **32**(3): 987-1009.

Grier, R. A., H. Thiruvengada, S. R. Ellis, P. Havig, K. S. Hale and J. G. Hollands (2012). "Augmented Reality – Implications toward Virtual Reality, Human Perception and Performance." Proceedings of the Human Factors and Ergonomics Society Annual Meeting **56**(1): 1351-1355.

Gu, F., B. Ma, J. Guo, P. A. Summers and P. Hall (2017). "Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study." Waste Management **68**: 434-448.

Han, D., H. Nie, J. Chen and M. Chen (2018). "Dynamic obstacle avoidance for manipulators using distance calculation and discrete detection." Robotics and Computer-Integrated Manufacturing **49**: 98-104.

Hao, J., X. Chen, H. Liu and S. Ye (2018). "A novel process planning algorithm for additive and subtractive manufacturing based on skeleton tree matching." Rapid Prototyping Journal **24**(2): 441-462.

Heyes, G., M. Sharmina, J. M. F. Mendoza, A. Gallego-Schmid and A. Azapagic (2018). "Developing and implementing circular economy business models in service-oriented technology companies." Journal of Cleaner Production **177**: 621-632.

Huang, S., Y. Guo, S. Zha, F. Wang and W. Fang (2017). "A Real-time Location System Based on RFID and UWB for Digital Manufacturing Workshop." Procedia CIRP **63**: 132-137.

Hughes, R. (2017). "The EU Circular Economy Package – Life Cycle Thinking to Life Cycle Law?" Procedia CIRP **61**: 10-16.

Ijomah, W. L., C. A. McMahon, G. P. Hammond and S. T. Newman (2007). "Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development." International Journal of Production Research **45**(18-19): 4513-4536.

International Organization for Standardization (2016). ISO/TS 15066:2016 Robots and robotic devices - Collaborative robots.

International Telecommunication Union (2012). Overview of the Internet of things. Global information infrastructure, Internet protocol aspects and next-generation networks, International Telecommunication Union.

Ivezic, N., B. Kulvatunyou and V. Srinivasan (2014). "On Architecting and Composing Through-life Engineering Information Services to Enable Smart Manufacturing." Procedia CIRP **22**: 45-52.

Jensen, J. P. and A. Remmen (2017). "Enabling Circular Economy Through Product Stewardship." Procedia Manufacturing **8**: 377-384.

Jiaping, X., L. Z. June, Y. Yong and L. Ling (2015). "Dynamic acquisition pricing policy under uncertain remanufactured-product demand." Industrial Management & Data Systems **115**(3): 521-540.

Jin, M., R. Tang, Y. Ji, F. Liu, L. Gao and D. Huisingh (2017). "Impact of advanced manufacturing on sustainability: An overview of the special volume on advanced manufacturing for sustainability and low fossil carbon emissions." Journal of Cleaner Production **161**: 69-74.

Jose, R. and S. Ramakrishna (2018). "Materials 4.0: Materials big data enabled materials discovery." Applied Materials Today **10**: 127-132.

Khaitan, S. K. and J. D. McCalley (2015). "Design Techniques and Applications of Cyberphysical Systems: A Survey." IEEE Systems Journal **9**(2): 350-365.

Kiritsis, D. (2011). "Closed-loop PLM for intelligent products in the era of the Internet of things." Computer-Aided Design **43**(5): 479-501.

Larsson, J. K. J. (2018). "Digital innovation for sustainable apparel systems: Experiences based on projects in textile value chain development." Research Journal of Textile and Apparel **22**(4): 370-389.

Lazarevic, D. and H. Valve (2017). "Narrating expectations for the circular economy: Towards a common and contested European transition." Energy Research & Social Science **31**: 60-69.

Lejon, E. and P. Jeppsson (2015). "Integrating Use Phase Information and Virtual Product Representation to Support Functional Products." Procedia CIRP **38**: 204-209.

Li, J., M. Barwood and S. Rahimifard (2018). "Robotic disassembly for increased recovery of strategically important materials from electrical vehicles." Robotics and Computer-Integrated Manufacturing **50**: 203-212.

Li, Q., H. Luo, P.-X. Xie, X.-Q. Feng and R.-Y. Du (2015). "Product whole life-cycle and omni-channels data convergence oriented enterprise networks integration in a sensing environment." Computers in Industry **70**: 23-45.

Liu, M. Z., C. H. Liu, M. G. Ge, Y. Zhang and Q. H. Zhu (2016). "Remanufacturing in Industry 4.0." Frontiers of Engineering Management **3**(2): 144-146.

Liu, S., G. Zhang and L. Wang (2018). "IoT-enabled Dynamic Optimisation for Sustainable Reverse Logistics." Procedia CIRP **69**: 662-667.

Liu, Z., T. Li, Q. Jiang and H. Zhang (2014). "Life Cycle Assessment-based Comparative Evaluation of Originally Manufactured and Remanufactured Diesel Engines." Journal of Industrial Ecology **18**(4): 567-576.

Lukman, R. K., P. Glavič, A. Carpenter and P. Virtič (2016). "Sustainable consumption and production – Research, experience, and development – The Europe we want." Journal of Cleaner Production **138**: 139-147.

Madslien, J. (2018). "FEATURE: Digital twins – predictive maintenance 'gets rid of the human factor'." Retrieved 01/08/2018, from https://www.imeche.org/news/news-article/feature-digital-twins-predictive-maintenance-'gets-rid-of-the-human-factor?utm_campaign=728003_DV_Manufacturing-update_Aug18&utm_medium=email&utm_source=imeche&dm_i=3X32,FLQB,3KQFYL,1NQVA,1.

Majeed, A., J. Lv and T. Peng (2018). "A framework for big data driven process analysis and optimization for additive manufacturing." Rapid Prototyping Journal.

Man, J. C. d. and J. O. Strandhagen (2017). "An Industry 4.0 Research Agenda for Sustainable Business Models." Procedia CIRP **63**: 721-726.

Marconi, M., F. Gregori, M. Germani, A. Papetti and C. Favi (2018). "An approach to favor industrial symbiosis: the case of waste electrical and electronic equipment." Procedia Manufacturing **21**: 502-509.

Marvel, J. A. and R. Norcross (2017). "Implementing Speed and Separation Monitoring in Collaborative Robot Workcells." Robot Comput Integr Manuf **44**: 144-155.

McFarland, R., C. Reise, A. Postawa and G. Seliger (2013). "Learnstruments in value creation and learning centered workplace design. Univ." Verl. der TU, Berlin.

Meng, K., P. Lou, X. Peng and V. Prybutok (2016). "A hybrid approach for performance evaluation and optimized selection of recoverable end-of-life products in the reverse supply chain." Computers & Industrial Engineering **98**: 171-184.

Menn, J. P., B. M. Duc, B. C. Müller and G. Seliger (2017). "Language Independent Transfer of Assembly Knowledge." Procedia Manufacturing **8**: 495-502.

Menn, J. P., F. Sieckmann, H. Kohl and G. Seliger (2018). "Learning process planning for special machinery assembly." Procedia Manufacturing **23**: 75-80.

Menn, J. P., C. Ulbrich and G. Seliger (2018a). "First proof of concept for language independent learnstruments in special machinery assembly." Procedia Manufacturing **21**: 454-461.

Meziane, R., M. J. D. Otis and H. Ezzaidi (2017). "Human-robot collaboration while sharing production activities in dynamic environment: SPADER system." Robotics and Computer-Integrated Manufacturing **48**: 243-253.

Mircheski, I. and T. Rizov (2017). "Improved Nondestructive Disassembly Process using Augmented Reality and RFID Product/Part Tracking." Tem Journal-Technology Education Management Informatics **6**(4): 671-677.

Mircheski, I. and T. Rizov (2018). "NONDESTRUCTIVE DISASSEMBLY PROCESS OF TECHNICAL DEVICE SUPPORTED WITH AUGMENTED REALITY AND RFID TECHNOLOGY." Acta Technica Corviniensis - Bulletin of Engineering **11**(2): 39-43.

Mourtzis, D., M. Doukas and D. Bernidaki (2014). "Simulation in Manufacturing: Review and Challenges." Procedia CIRP **25**: 213-229.

Muftooh, U. R. S., W. L. Ijomah, G. I. Dobie, M. Hafeez, S. G. Pierce, W. Ion, C. Mineo and C. N. MacLeod (2018). "Low cost three-dimensional virtual model construction for remanufacturing industry." Journal of Remanufacturing: 1-11.

Müller, B. C., T. D. Nguyen, Q.-V. Dang, B. M. Duc, G. Seliger, J. Krüger and H. Kohl (2016b). "Motion Tracking Applied in Assembly for Worker Training in different Locations." Procedia CIRP **48**: 460-465.

Müller, B. C., C. Reise, B. M. Duc and G. Seliger (2016a). "Simulation-games for Learning Conducive Workplaces: A Case Study for Manual Assembly." Procedia CIRP **40**: 353-358.

Müller, J. R., M. Panarotto, J. Malmqvist and O. Isaksson (2018). "Lifecycle design and management of additive manufacturing technologies." Procedia Manufacturing **19**: 135-142.

Murmura, F. and L. Bravi (2018). "Additive manufacturing in the wood-furniture sector: Sustainability of the technology, benefits and limitations of adoption." Journal of Manufacturing Technology Management **29**(2): 350-371.

Musa, A., A. Gunasekaran, Y. Yusuf and A. Abdelazim (2014). "Embedded devices for supply chain applications: Towards hardware integration of disparate technologies." Expert Systems with Applications **41**(1): 137-155.

Ness, D., J. Swift, D. C. Ranasinghe, K. Xing and V. Soebarto (2015). "Smart steel: new paradigms for the reuse of steel enabled by digital tracking and modelling." Journal of Cleaner Production **98**: 292-303.

Nguyen, T., L. Zhou, V. Spiegler, P. Ieromonachou and Y. Lin (2017). "Big data analytics in supply chain management: A state-of-the-art literature review." Computers & Operations Research.

Nowakowski, P. (2018). "A novel, cost efficient identification method for disassembly planning of waste electrical and electronic equipment." Journal of Cleaner Production **172**: 2695-2707.

Ondemir, O. and S. M. Gupta (2014). "Quality management in product recovery using the Internet of Things: An optimization approach." Computers in Industry **65**(3): 491.

Osti, F., A. Ceruti, A. Liverani and G. Caligiana (2017). "Semi-automatic Design for Disassembly Strategy Planning: An Augmented Reality Approach." Procedia Manufacturing **11**: 1481-1488.

Pagoropoulos, A., D. C. A. Pigosso and T. C. McAloone (2017). "The Emergent Role of Digital Technologies in the Circular Economy: A Review." Procedia CIRP **64**: 19-24.

Park, S.-C. (2017). "The Fourth Industrial Revolution and implications for innovative cluster policies." AI & Society: 1-13.

Preston, F. (2012). A Global Redesign? Shaping the Circular Economy. Energy, Environment and Resource Governance. London, UK, The Royal Institute of International Affairs. **EERG BP 2012/02**.

Raihanian Mashhadi, A. and S. Behdad (2018). "Ubiquitous Life Cycle Assessment (U-LCA): A Proposed Concept for Environmental and Social Impact Assessment of Industry 4.0." Manufacturing Letters **15**: 93-96.

Ranky, P. G. (2001). "Trends and R&D in virtual and robotized product disassembly." Industrial Robot: the international journal of robotics research and application **28**(6): null.

Rejeski, D., F. Zhao and Y. Huang (2018). "Research needs and recommendations on environmental implications of additive manufacturing." Additive Manufacturing **19**: 21-28.

Ren, S., Y. Zhang, Y. Liu, T. Sakao, D. Huisingh and C. M. V. B. Almeida (2019). "A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions." Journal of Cleaner Production **210**: 1343-1365.

Romero, D. and O. Noran (2017). "Towards Green Sensing Virtual Enterprises: Interconnected Sensing Enterprises, Intelligent Assets and Smart Products in the Cyber-Physical Circular Economy." IFAC-PapersOnLine **50**(1): 11719-11724.

Romero, D. and F. Vernadat (2016). "Enterprise information systems state of the art: Past, present and future trends." Computers in Industry **79**: 3-13.

Roy, R., R. Stark, K. Tracht, S. Takata and M. Mori (2016). "Continuous maintenance and the future – Foundations and technological challenges." CIRP Annals **65**(2): 667-688.

Ruggeri, S., G. Fontana, V. Basile, M. Valori and I. Fassi (2017). "Micro-robotic Handling Solutions for PCB (re-)Manufacturing." Procedia Manufacturing **11**: 441-448.

Ryen, E. G., G. Gaustad, C. W. Babbitt and G. Babbitt (2017). "Ecological foraging models as inspiration for optimized recycling systems in the circular economy." Resources, Conservation and Recycling.

Saidani, M., B. Yannou, Y. Leroy and F. Cluzel (2017). "Heavy vehicles on the road towards the circular economy: Analysis and comparison with the automotive industry." Resources, Conservation and Recycling.

Santochi, M., G. Dini and F. Failli (2002). "Computer Aided Disassembly Planning: State of the Art and Perspectives." CIRP Annals **51**(2): 507-529.

Schlüter, M., C. Niebuhr, J. Lehr and J. Krüger (2018). "Vision-based Identification Service for Remanufacturing Sorting." Procedia Manufacturing **21**: 384-391.

Schmidt, B., L. Wang and D. Galar (2017). "Semantic Framework for Predictive Maintenance in a Cloud Environment." Procedia CIRP **62**: 583-588.

Schweichhart, K. (2016). RAMI4.0 –Reference Architecture Model Industry 4.0. Digitising Manufacturing, Platform Industrie 4.0.

Segovia, D., H. Ramírez, M. Mendoza, M. Mendoza, E. Mendoza and E. González (2015). "Machining and Dimensional Validation Training Using Augmented Reality for a Lean Process." Procedia Computer Science **75**: 195-204.

Seuring, S. and S. Gold (2012). "Conducting content-analysis based literature reviews in supply chain management." Supply Chain Management: An International Journal **17**(5): 544-555.

Siddique, Z. and D. W. Rosen (1997). "Virtual prototyping approach to product disassembly reasoning." COMPUT AIDED DES **29**(12): 847-860.

SMMT (2017). 2017 UK Automotive Sustainability Report. London, UK, The Society of Motor Manufacturers and Traders Limited.

Stark, R., H. Grosser, B. Beckmann-Dobrev and S. Kind (2014). "Advanced Technologies in Life Cycle Engineering." Procedia CIRP **22**: 3-14.

Statista. (2018). "Smartphone sales worldwide 2007-2017." Retrieved 10/09/2018, from https://www.statista.com/statistics/263437/global-smartphone-sales-to-end-users-since-2007/.

Stock, T. and G. Seliger (2016). "Opportunities of Sustainable Manufacturing in Industry 4.0." Procedia CIRP **40**: 536-541.

Takata, S., H. Isobe and H. Fujii (2001). "Disassembly Operation Support System with Motion Monitoring of a Human Operator." CIRP Annals **50**(1): 305-308.

Takata, S., F. Kirnura, F. J. A. M. van Houten, E. Westkamper, M. Shpitalni, D. Ceglarek and J. Lee (2004). "Maintenance: Changing Role in Life Cycle Management." CIRP Annals **53**(2): 643-655.

Tao, F., Y. Wang, Y. Zuo, H. Yang and M. Zhang (2016). "Internet of Things in product life-cycle energy management." Journal of Industrial Information Integration **1**: 26-39.

Tolio, T., A. Bernard, M. Colledani, S. Kara, G. Seliger, J. Duflou, O. Battaia and S. Takata (2017). "Design, management and control of demanufacturing and remanufacturing systems." CIRP Annals **66**(2): 585-609.

Tornese, F., J. A. Pazour, B. K. Thorn, D. Roy and A. L. Carrano (2018). "Investigating the environmental and economic impact of loading conditions and repositioning strategies for pallet pooling providers." Journal of Cleaner Production **172**: 155-168.

Tsai, C.-W., C.-F. Lai, H.-C. Chao and A. V. Vasilakos (2015). "Big data analytics: a survey." Journal of Big Data **2**(1).

Uhlemann, T. H. J., C. Lehmann and R. Steinhilper (2017). "The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0." Procedia CIRP **61**: 335-340.

Uhlemann, T. H. J., C. Schock, C. Lehmann, S. Freiberger and R. Steinhilper (2017a). "The Digital Twin: Demonstrating the Potential of Real Time Data Acquisition in Production Systems." Procedia Manufacturing **9**: 113-120.

UN General Assembly (2015). "Transforming Our World: The 2030 Agenda for Sustainable Development A/RES/70/1."

United Nations. (no date). "Sustainable Development Goals." Retrieved 20/12/2018, from https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

Viet, N. Q., B. Behdani and J. Bloemhof (2018). "The value of information in supply chain decisions: A review of the literature and research agenda." Computers & Industrial Engineering **120**: 68-82.

Vikas, K., A. Marlene, B. Arijit and G.-R. J. Arturo (2016). "Managing reverse exchanges in service supply chains." Supply Chain Management: An International Journal **21**(2): 157-165.

Vongbunyong, S., P. Vongseela and J. Sreerattana-aporn (2017). "A Process Demonstration Platform for Product Disassembly Skills Transfer." Procedia CIRP **61**: 281-286.

Wang, L. (2013). "Machine availability monitoring and machining process planning towards Cloud manufacturing." CIRP Journal of Manufacturing Science and Technology **6**(4): 263-273.

Wang, L. and X. V. Wang (2018). "Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0." International Journal of Production Research: 1-11.

Wang, L., X. V. Wang, L. Gao and J. Váncza (2014). "A cloud-based approach for WEEE remanufacturing." CIRP Annals **63**(1): 409-412.

Wang, X., S. K. Ong and A. Y. C. Nee (2018). "A comprehensive survey of ubiquitous manufacturing research." International Journal of Production Research **56**(1-2): 604-628.

Wang, X. V. and L. H. Wang (2017). "A cloud-based production system for information and service integration: an internet of things case study on waste electronics." Enterprise Information Systems **11**(7): 952-968.

Wegener, K., S. Andrew, A. Raatz, K. Dröder and C. Herrmann (2014). "Disassembly of Electric Vehicle Batteries Using the Example of the Audi Q5 Hybrid System." Procedia CIRP **23**: 155-160.

Wegener, K., W. H. Chen, F. Dietrich, K. Dröder and S. Kara (2015). "Robot Assisted Disassembly for the Recycling of Electric Vehicle Batteries." Procedia CIRP **29**: 716-721.

Westkämper, E. (2003). "Assembly and Disassembly Processes in Product Life Cycle Perspectives." CIRP Annals **52**(2): 579-588.

Xiao, L., W. Liu, Q. Guo, L. Gao, G. Zhang and X. Chen (2018). "Comparative life cycle assessment of manufactured and remanufactured loading machines in China." Resources, Conservation and Recycling **131**: 225-234.

Yawei, X., D. Lihong, W. Haidou, J. Jiannong and L. Yongxiang (2017). "A review of passive self-sensing tag." Sensor Review **37**(3): 338-345.

Yeo, N. C. Y., H. Pepin and S. S. Yang (2017). "Revolutionizing Technology Adoption for the Remanufacturing Industry." Procedia CIRP **61**: 17-21.

Yi, H.-C. and J. W. Park (2015). "Design and Implementation of an End-of-Life Vehicle Recycling Center Based on IoT (Internet of Things) in Korea." Procedia CIRP **29**: 728-733.

Zhang, J., P. Wang, R. X. Gao and R. Yan (2018). "An Image Processing Approach to Machine Fault Diagnosis Based on Visual Words Representation." Procedia Manufacturing **19**: 42-49.

Zhang, Y., S. Liu, Y. Liu, H. Yang, M. Li, D. Huisingh and L. Wang (2018a). "The 'Internet of Things' enabled real-time scheduling for remanufacturing of automobile engines." Journal of Cleaner Production **185**: 562-575.

Zhang, Y., S. Ren, Y. Liu, T. Sakao and D. Huisingh (2017). "A framework for Big Data driven product lifecycle management." Journal of Cleaner Production **159**: 229-240.

Zhang, Y., S. Ren, Y. Liu and S. Si (2017a). "A big data analytics architecture for cleaner manufacturing and maintenance processes of complex products." Journal of Cleaner Production **142**: 626-641.

Zhang, Y., G. Zhang, W. Du, J. Wang, E. Ali and S. Sun (2015). "An optimization method for shopfloor material handling based on real-time and multi-source manufacturing data." International Journal of Production Economics **165**: 282-292.

Zheng, Z., W. Xu, Z. Zhou, D. T. Pham, Y. Qu and J. Zhou (2017). "Dynamic Modeling of Manufacturing Capability for Robotic Disassembly in Remanufacturing." Procedia Manufacturing **10**: 15-25.

Zhou, C., X. Liu, F. Xue, H. Bo and K. Li (2018). "Research on static service BOM transformation for complex products." Advanced Engineering Informatics **36**: 146-162.

Zwolinski, P., S. Tichkiewitch and A. Sghaier (2007). "The Use of Virtual Reality Techniques during the Design Process: from the Functional Definition of the Product to the Design of its Structure." CIRP Annals **56**(1): 135-138.