Smart remanufacturing

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DOI:
10.1108/JMTM-06-2019-0205

Smart Remanufacturing: A Review and Research Framework

Purpose

To review the state-of-the-art in smart remanufacturing, highlighting key elements of an Industry 4.0 future that supports circular economy principles, and offer a conceptual framework and a research agenda for transitioning to smart manufacturing.

Approach

The Scopus, Web of Science and Science Direct databases and search terms "Industry 4.0", "Internet of Things", "Smart manufacturing" and "Remanufacturing" were used to identify and select publications that had evidence of a relationship between those keywords. The 329 selected papers were reviewed with respect to the triple bottom line (economic, social and environmental). The study benefited from advanced text quantitative processing using NVivo software and a complete manual qualitative assessment.

Findings

Changes in product ownership models will affect the remanufacturing industry, with the growth of product-service-systems seen as an opportunity to re-circulate resources and create value. This is being supported by changes in society, user expectations and workforce attributes. Key to the success of remanufacturing in an Industry 4.0 future is the uptake of existing and emerging digital technologies to shorten and strengthen links between product manufacturers, users and remanufacturers.

Originality

Remanufacturing is recognised as a key circular economy strategy, which in turn is an important research area for development in our society. This article is the first to study "smart remanufacturing" for the circular economy. Its uniqueness lies in its focus on the remanufacturing industry and the sustainable application of Industry 4.0 enablers. The findings are used to create a framework that links to the research agenda needed to realise smart remanufacturing.

1.1 Key Words:

Remanufacturing; Industry 4.0; Internet of Things; Smart Remanufacturing; Digital Remanufacturing; Cyber-Physical Systems; Circular Economy

Nomenclature

AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
BoL	Beginning of Life
CE	Circular Economy
CM	Cloud Manufacturing
CPS	Cyber Physical Systems
CSF	Critical Success Factor
D4S	Design for Sustainability
DfAM	Design for Additive Manufacturing
DfD	Design for Disassembly
DfR	Design for Remanufacture
DfS	Design for Service
DT	Digital Twins
EoL	End of Life
ICT	Information and Communication Technology
I4.0	Industry 4.0
IoT	Internet of Things
LCA	Life Cycle Analysis
MoL	Middle of Life
OEM	Original Equipment Manufacturer
PPU	Pay Per Use
PSS	Product Service System
RBoM	Remanufacturing Bill of Materials
RFID	Radio Frequency Identification
RMS	Reconfigurable Manufacturing System
SME	Small-Medium Enterprises
VR	Virtual Reality
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

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 circular economy (CE) of which remanufacturing is a key strategy (Preston 2012). As one of the nine CE strategies (Potting 2016), remanufacturing is defined as the "steps required to change the product into as-new with at least equivalent performance and warranty of new" (British Standards Institution 2010). It has the potential to be worth €90bn to the EU economy by 2030 (Oakdene Hollins 2018) making it a particularly interesting subject for industry-based readers.

Industry 4.0 (I4.0) builds on the three previous revolutions with the intelligent networking of machines and processes (Federal Ministry for Economic Affairs and Energy 2019). The Internet of Things (IoT) is an infrastructure that connects existing and emerging, real and virtual technologies enabling advanced services (International Telecommunication Union 2012). I4.0 and IoT are closely interconnected (Schweichhart 2016), and their hyper automation and connectivity enables the realisation of smart factories (Stock and Seliger 2016) built on Cyber Physical Systems (CPS) (Khaitan and McCalley 2015) operated by artificial intelligence (AI), IoT, big data and robotics (Park 2017). In manufacturing, the application of smart factory principles and technologies is already underway (Ghobakhloo 2019) driven by a number of Original Equipment Manufacturers (OEM) (Tolio et al. 2017), and research consortia (Bueno et al. 2017). Remanufacturers can learn from these applications but as they generally operate in a lower technology environment (Butzer and Schötz 2016) with different management strategies, a smart factory vision specifically for this industry in needed.

Whist there has been an increase in the attention given to remanufacturing (Yang et al. 2014), and frameworks on the application of I4.0 technologies and their potential to support the CE are emerging (Kamble et al. 2018), the remanufacturing industry is rarely the main focus of research. The present study will look to fill this gap by providing a framework for remanufacturing to support the transition from a traditionally highly manual and unstable industry, to an automated, data-driven, smart one using I4.0. In order to build the framework, a firm understanding of key I4.0 technologies and their potential impact on the industry is required.

The next section presents the review methodology and an overview of findings (section 2). Identified trends in the use of I4.0 technologies for remanufacturing are outlined in section 3. Section 4 explores the impact of I4.0 technologies in remanufacturing for the CE categorised according to economic, social and environmental factors. Section 5 proposes a framework and research agenda to support the digitalisation of remanufacturing for the CE. Section 5.2 concludes the paper.

2 Literature Review

A methodical approach to this inductive review (Miles et al. 2020) was adopted to help develop a reliable knowledge base (Tranfield et al. 2003), generate an early research question and survey the state-of-the-art, before proposing future hypotheses and a research agenda as outputs.

2.1 Research Methodology

A systematic process (Durach et al. 2017) was used, starting with an open-dated search of three academic databases. To avoid missing key literature due to different labelling of the same concepts, search terms included "Industry 4.0", "Internet of Things" OR "Smart Manufacturing" AND "Remanufactur". Figure 1 summarises the inclusion and exclusion criteria, processing, cleansing and assessment.

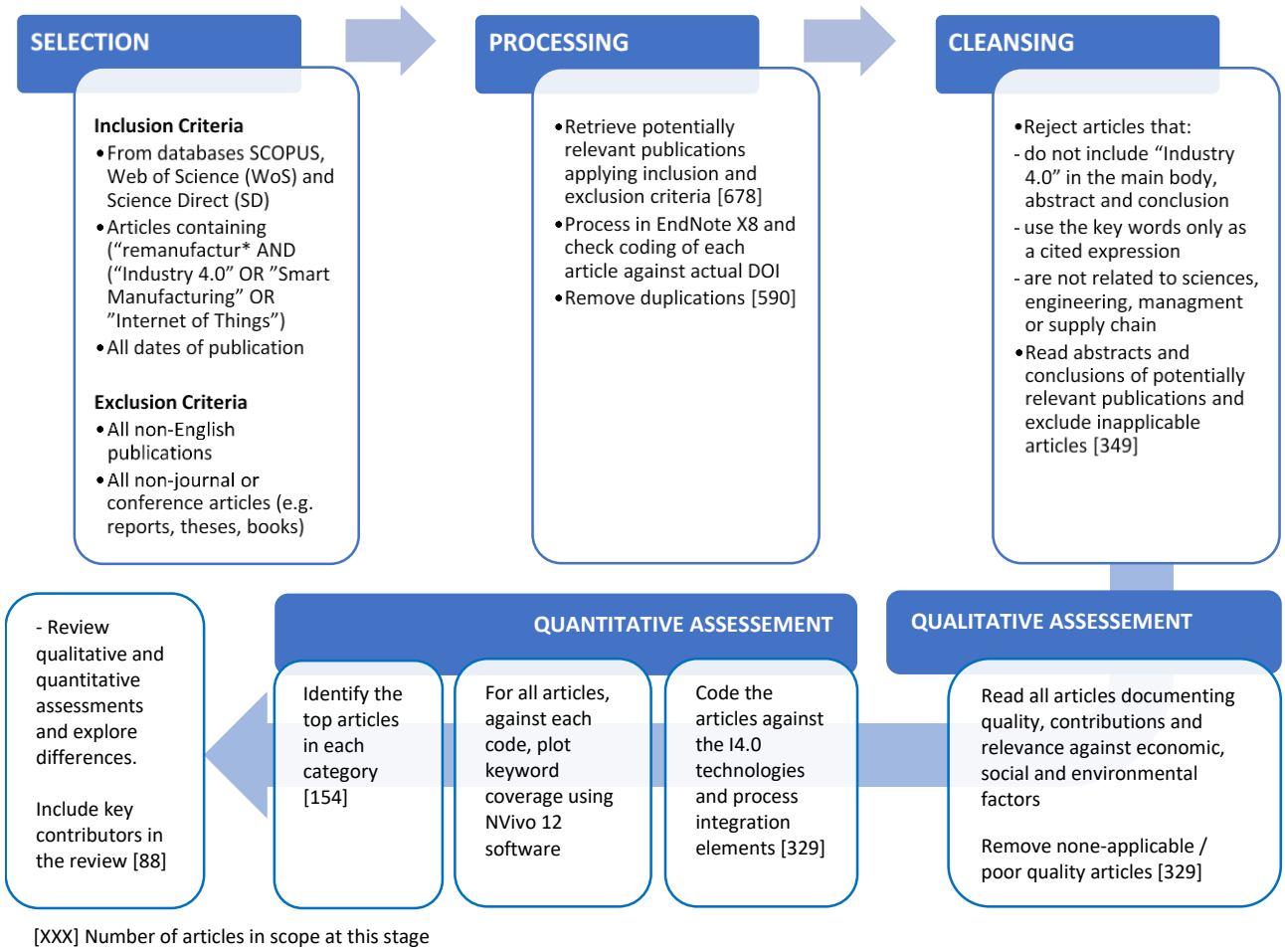

Figure 1 - Literature review process adapted from Durach et al. (2017)

The inclusion of at least one keyword in the body of the text was critical to its retention. Articles that did not contain "remanufacturing" in the body of the text were not automatically excluded as there is currently a lower level of smart enablers used in remanufacturing compared to other smart-circular strategies (Alcayaga

et al. 2019) and lessons can be learned for application in this emerging area. However, articles that did not contain "Industry 4.0", "Smart Manufacturing" or "Internet of Things" were rejected.

This resulted in the identification of 349 pertinent articles from 2011 to 2020. (Although the search was completed in August 2019, it uncovered in-press articles due to appear in 2020.) Figure 2 shows the distribution of these articles and the year-on-year growth in the combined utilisation of the keywords, justifying the timeliness of this research. (The 2019/20 bars are hashed due to the mid-year search.)

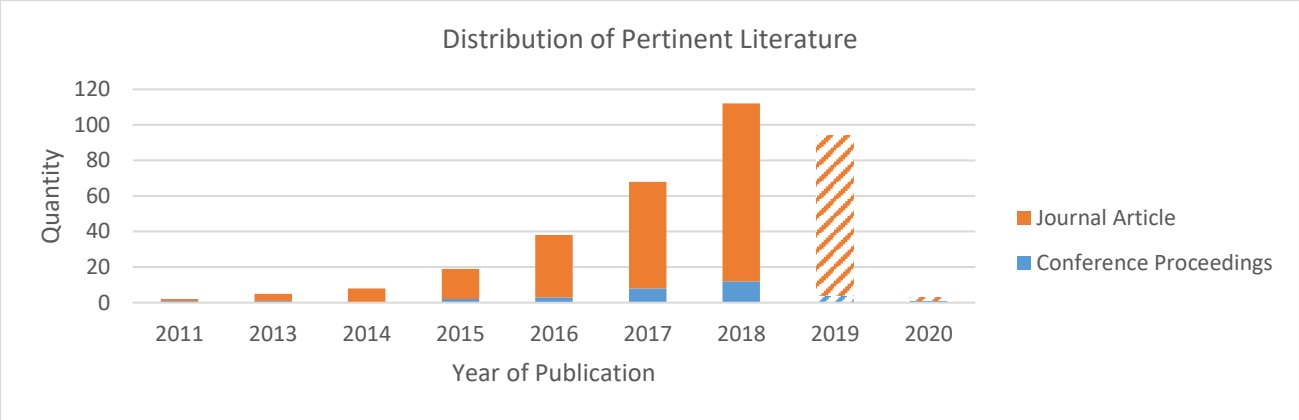

Figure 2 - Distribution of relevant articles identified in the keyword search August 2019, post cleansing

Figure 3 shows that the leading journal outlets in this field are Procedia CIRP, Journal of Cleaner Production and Procedia Manufacturing.

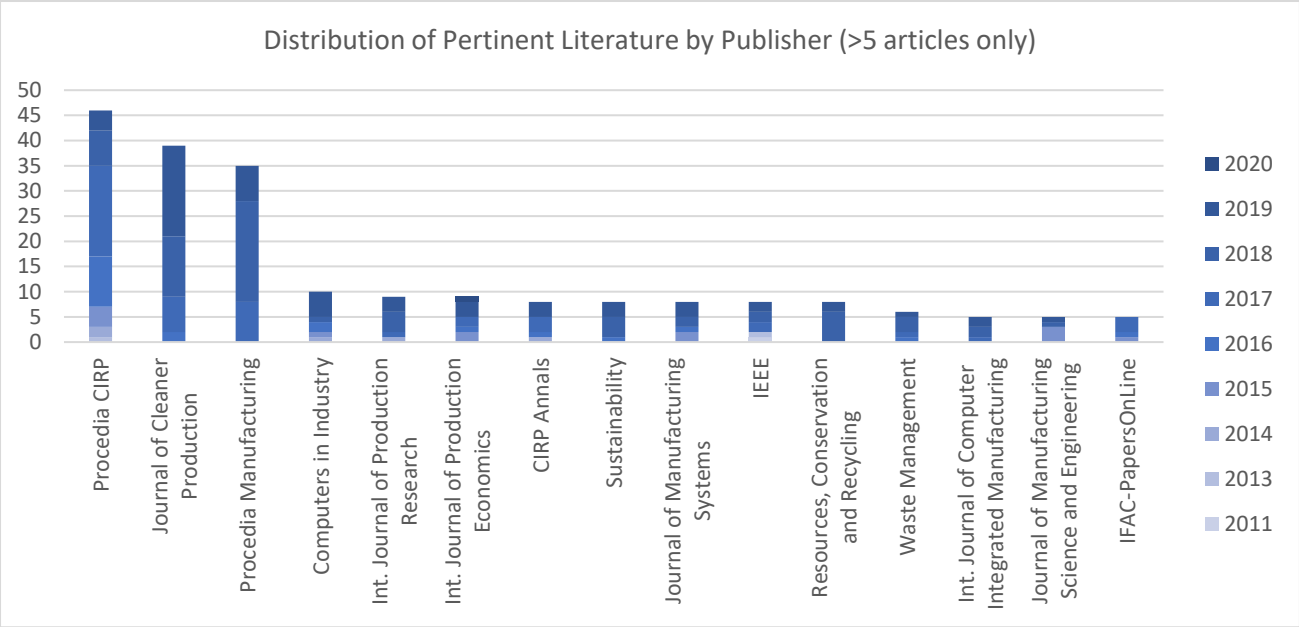

Figure 3 - Distribution of relevant literature by journal outlet

329 of the 349 articles were cleansed for coding in NVivo12 to provide a quantitative assessment of contribution based on the coverage of the database search keywords in addition to I4.0 technologies and

process integration elements adapted from Kamble et al. (2018)'s sustainability framework. 20 articles were either of poor quality, unavailable or not readable to NVivo12. This assessment offered an insight into the key themes and contributors in this field. Remaining articles were ranked against the different search codes based on their individual coverage as 1st-5th= highly relevant, 6th-10th= relevant, 11th-20th= mentioned. The coverage of keywords was measured. Additionally, a qualitative assessment of the same articles was conducted by the two authors involved. Differences of opinion were rare and resolved through discussion.

2.2 Descriptive Findings

From the quantitative assessment of each code 154 articles appeared at least once in the top 20 signifying the sporadic distribution of the findings. The top 20 articles identified as containing the greatest coverage of all coded search terms are presented in Figure 4 with their weighted relevance to each coding term (as described in columns "Keywords for Coding") documented in Table 1.

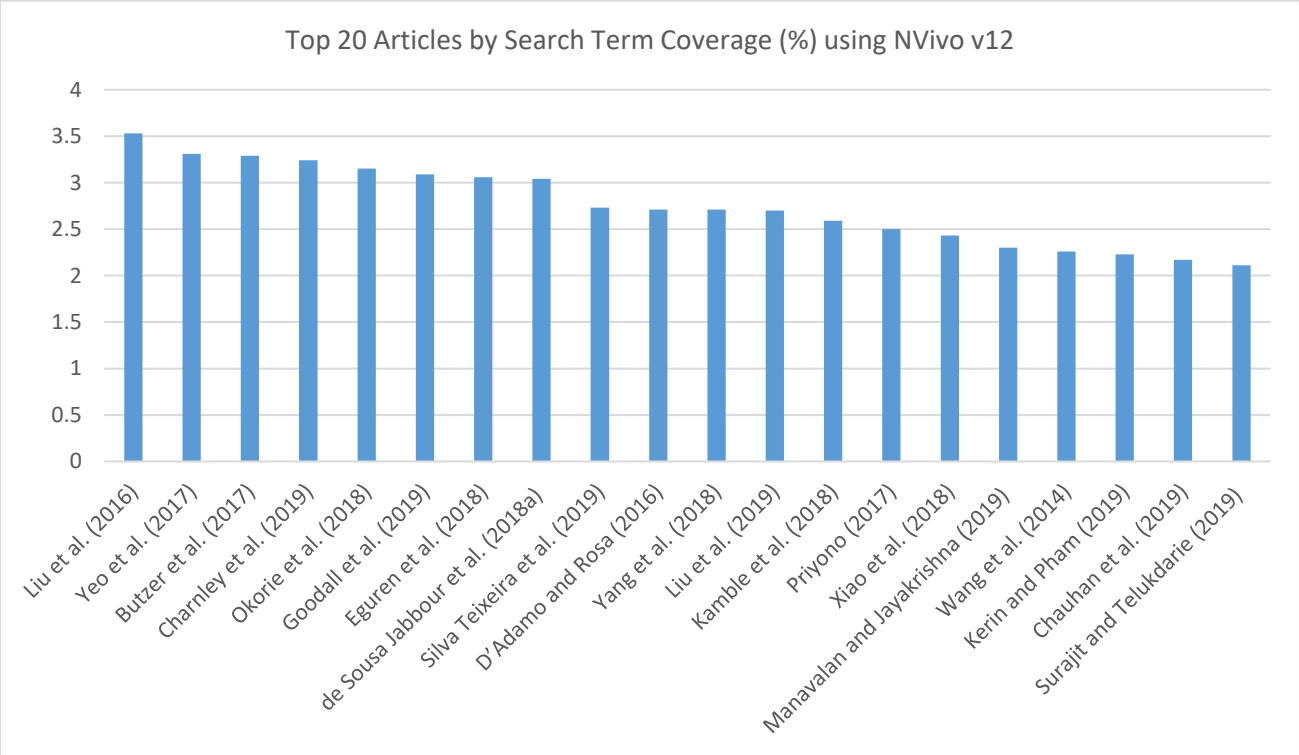

Figure 4 - Key articles based on quantitative assessment using coding methods and NVivo software

Table 1 - Coding table showing the top 20 articles by total coverage only

KEY Highly relevant ✓✓✓ Relevant ✓✓ Mentioned ✓		Keywords for Coding													
Database search terms			*	*	*	*									
Ranking	Article	Circular economy, CE	Remanufactur(e/ed/ing)	Industry 4.0, I4.0	Smart (re)manufacturing	Internet of things, IoT	Robot	Additive manufacturing, AM, 3D printing	Big data analytics, BDA	Cloud Computing, CC, Cloud manufacturing, CM	Simulation, prototyping	Augmented reality, AR	Advanced materials, self-healing	Human-(machine/robot) collaboration, HMC, HRC	System(s) integration, process integration
1	Liu et al. (2016)		✓✓✓	✓✓✓											
2	Yeo et al. (2017)		✓✓✓				✓					✓			
3	Butzer et al. (2017)		✓✓✓	✓								✓✓✓			
4	Charnley et al. (2019)		✓✓								✓✓				
5	Okorie et al. (2018)		✓✓✓												
6	Goodall et al. (2019)		✓								✓✓✓				
7	Eguren et al. (2018)		✓✓✓												
8	de Sousa Jabbour et al. (2018a)			✓✓✓	✓	✓✓✓		✓		✓					
9	Silva Teixeira et al. (2019)		✓								✓✓✓				
10	Yang et al. (2018)		✓✓		✓✓										
11	Kamble et al. (2018)			✓✓✓	✓✓				✓		✓	✓✓			✓✓✓
12	Xiao et al. (2018)		✓✓												
13	Manavalan and Jayakrishna (2019)	✓✓✓		✓		✓									
14	Wang et al. (2014)		✓							✓✓					
15	Kerin and Pham (2019)		✓				✓					✓✓			
16	Chauhan et al. (2019)	✓		✓✓✓											
17	Surajit and Telukdarie (2019)			✓								✓		✓	
18	Ding et al. (2018)		✓✓						✓✓						
19	Pagoropoulos et al. (2017)	✓✓✓				✓			✓						
20	Rajput and Singh (2019)			✓✓✓		✓									✓✓
NOTE: Due to limited findings the codes "Advanced materials, self-healing" and "Human-(machine/robot) collaboration, HMC, HRC" were ranked differently as follows: 1st-2nd= highly relevant, 3rd-4th= relevant, 5th-8th = mentioned.															

Interestingly, the article identified as having the greatest search term coverage was Liu et al. (2016) who compared I4.0 for remanufacturing with blood circulation systems. During the qualitative assessment the same article was deemed to be not so relevant to this review. This contradictory result suggests caution should be employed when performing quantitative data assessments alone in this emerging area and backs the authors decision to read all articles in parallel to provide qualitative input. In general, the two research

methods align. Findings suggest there is an increase in research being conducted in remanufacturing, I4.0 and the CE individually but there is no review that considers all three in detail.

In remanufacturing, Butzer et al. (2016) identify sector challenges and how these could be resolved with I4.0 technology but at a very high level, lacking thoroughness. Trends and gaps are documented (Kerin and Pham 2019) and detailed exploration of remanufacturing I4.0 is offered in specific applications (Wang et al. 2014, Yang et al. 2018), regions (Eguren et al. 2018) or both (Yeo et al. 2017, Xiao et al. 2018). A popular emerging sub-topic is remanufacturing process modelling with inputs from I4.0 technologies (Ding et al. 2018, Goodall et al. 2019). Outlying articles exist on advanced or self-healing materials, but as can be seen from the lack of rankings in this column, it is not a core research area. Away from remanufacturing, articles that synergise I4.0 and CE are focused on supply chain (Pagoropoulos et al. 2017, Manavalan and Jayakrishna 2019), its management (Chauhan et al. 2019, Rajput and Singh 2019, Surajit and Telukdarie 2019) or manufacturing. In manufacturing they generally report on the benefits before presenting research agendas, models, architectures, roadmaps and/or frameworks for businesses or researchers to follow (Carvalho et al. 2018, de Sousa Jabbour et al. 2018a, de Sousa Jabbour 2019, Nascimento et al. 2019). The output of Man and Strandhagen (2017) is similar, but interestingly they are more cautious in their appraisal of I4.0. The framework by Kamble et al. (2018) was adapted to form the search term codes so there is little surprise that it makes the top 20 but it does little more than tabulate I4.0 technologies (that are better presented in other works) and the I4.0 principles from Carvalho *et al.* (2018). Ghobakhloo (2018) offers subtly different I4.0 technologies and principles in their architecture and roadmap for transitioning but again this is for the manufacturing sector. Additionally with reference to Charnley et al. (2019) and Okorie et al. (2018), (4th and 5th respectively) both articles are deemed relevant, but it is another article that they co-authored (Okorie et al. 2018) that the qualitative assessment identifies as the most interesting to this work. They extensively survey the state-of-art in CE-I4.0 methodologies on the 9R's (refusing, rethinking, reducing, reusing, repairing, remanufacturing, refurbishing, repurposing, recycling, and recovering) recommending a reduced scope, down from the 9R's for more detailed research, which underlines the need for this review. Whilst the above-mentioned articles are relevant (each in agreement that I4.0 businesses will increasingly rely on intelligent data to deliver new services), they do not exclusively explore "smart" remanufacturing in the CE. It is therefore assumed that they are only partly applicable.

The objective of this paper is to develop a research agenda to support the realisation of smart remanufacturing. The assumption that existing I4.0 manufacturing research is only partly applicable to remanufacturing generates new research questions – What aspects of the existing I4.0 technology and principles already researched are applicable but specific to remanufacturing? What is required to make remanufacturing smart and sustainable?

This article shall attempt to answer these questions following a summary of I4.0 technologies for remanufacturing (section 3) and the results of the literature review that is categorised using the triple bottom line (section 4). Key findings are noted throughout the article and registered using a hashtag and number, e.g. [#1]. These are then used to formulate the framework.

3 I4.0 Technologies for Remanufacturing

Smart remanufacturing technologies are already identified (Yang et al. 2018), in some cases demonstrated (Wang et al. 2018) and can be fitted to the product to be remanufactured or the equipment used in the remanufacturing process to optimise end-of-life (EoL) decision making (Kerin and Pham 2019). Interestingly, these identified technologies are not unique to remanufacturing. It is therefore prudent to explore the use of existing manufacturing technology to support remanufacturing activities (Ferrer and Clay Whybark 2000). The enabling technologies expected to maximise productivity growth include robotics, Additive Manufacturing (AM) methods, integrated with big data analytics, artificial intelligence (AI), sensors and advanced materials (Roos 2016). These will be surveyed in the next section for applications in remanufacturing.

3.1 The Enabling Technologies

The remanufacturing process is made up of many sub-processes including disassembly (All-Party Parliamentary Sustainable Resource Group 2014) and the development of smart robotic disassembly cells using intelligent sensing and real-time adaptation is identified as a key research topic (Ranky 2001). It is necessary to recognise disassembly is not simply the reverse of assembly as the product may be worn, fittings may be irreversible, partial disassembly only may be required and destructive operations can be considered (Touzanne et al. 2001). The optimal process varies depending on the product quality and desired outcome. As the application of algorithms in disassembly planning has been extensively reviewed (Wang et al. 2013), this will not be explored in this paper. However, it is worth noting that their integration with robotics and vision systems can be used to generate and apply disassembly sequences both off-line (ElSayed et al. 2010) and on-line (ElSayed et al. 2011). The optimism shown towards the use of robots for EoL product processing waivers over time (Lambert and Gupta 2004) due to the economies of scale and uncertainties in core quality. However, with the correct evaluation of both the application and the robot's capabilities (Rao et al. 2011, Zheng et al. 2017) robotised disassembly solutions can be realised (Huang et al. 2019).

Once disassembled, AM can be used to restore components (Böß et al. 2017, Yeo et al. 2017, Abdulrahman et al. 2018). Already well documented are the opportunities and limitations (Murmura and Bravi 2018), key methods and leading providers (Nickels 2016). However, there is a requirement to better appreciate the environmental implications of hybrid materials and structures, and the impact that customisation and IP of

AM parts have on remanufacturing processes (Rejeski et al. 2018). The design-for-remanufacturing (DfR) methodology for application at a product's beginning-of-life (BoL) could have an interesting sub-method – design-for-AM (DfAM) (Gebisa and Lemu 2017) supported by demonstration tools to capture and display the different life cycle implications (Müller et al. 2018).

Big data and AI solutions are generally packaged with other technologies for remanufacturing, including data carrying devices and identification labels (RFID, QR etc.) (Zlamparet et al. 2018). Once a core is identified, the remanufacturing process can benefit from an EoL database containing reverse logistics information. This can facilitate the tracking of component quality, quantity and location, and enable the determination of the best facility in which to remanufacture the product minimising environmental impact and optimising resource efficiencies and profits (Wang et al. 2018a). But there is a need for more research in the area of big data in reverse logistics and cloud-based systems for analysing the data collected on used products and improving the coordination of distributed supply chains (Nguyen et al. 2017). Work has started on developing an understanding of what type of data would benefit remanufacturers using encoding methods to simplify and record materials found in components on RFID tags with (Meng et al. 2016), or without (Nowakowski 2018), the need to link to databases and decision-making optimisation tools.

Sensors providing in-use real-time big data for manufacturing using data mining models could help explore hidden trends and life cycle knowledge (Zhang et al. 2017, Zhang et al. 2017a). Additionally, virtual Reality (VR) (Fox, 2016) and Augmented Reality (AR) (Kishita et al. 2018) have been recognised as enablers to remanufacturing in a CE for the aggregation and visualisation of information. In the future nothing will be manufactured until it has been designed and refined in cyberspace (Coates 2000) and the level of 'smartness' of a manufacturing enterprise is determined by the degree to which it has been digitally reflected (Kusiak 2018). The digital modelling of products or processes is not new but combining the real and virtual worlds and enabling their interaction is. This concept (digital twinning) is generating great and sustainable interest (Lu et al. 2020). Digital twins (DT) fuse real sensors and data (Diez-Olivan et al. 2019) to form representative virtual products or processes. Abramovici et al. (2017) focus primarily on the re-configuration potential of in-use products using DT but their work also has application in EoL remanufacturing. At the process level, the use of sensor-based tracking to capture real-time data on product manufacturing can support the generation of factory DT (Uhlemann et al. 2017), with data-driven simulation deemed suitable for modelling the complexities of remanufacturing operations (Negahban and Smith 2014, Goodall et al. 2019). These tools are particularly relevant to remanufacturing process design and are therefore included in the proposed framework [#1, #10]. However, research suggests there a need to further study big data and technology integration in a CE, including remanufacturing (Nguyen et al. 2017), with greater focus on the application of product data captured in previous life cycles on decision-making for future ones (Wang et al. 2018).

Advanced self-healing materials (Wang et al. 2015) and self-maintaining products (Takata et al. 2004) have implications for remanufacturing. They may change the demand, the processes and technology involved expedited by the Materials 4.0 paradigm (Jose and Ramakrishna 2018). Additionally these may offer improved sensors, systems, cameras and communication interfaces needed for faster data capturing and analysis (both requirements that need to be addressed to realise the technology revolution for remanufacturing (Uhlemann et al. 2017a)).

3.2 Integrating and Managing the Technologies

Whilst the technologies involved in manufacturing and remanufacturing may be similar, planning and control in the latter is more complicated due to inherent business variabilities (Guide et al. 2000). The remanufacturer can work to minimise the variability or allow it to exist and install flexible solutions (Huang et al. 2019). Uncertainties in EoL product quality and quantity make disassembly in remanufacturing challenging to automate (Vongbunyong et al. 2017). A high level of certainty of product quality can support confident data-driven decision-making in remanufacturing (Charnley et al. 2019), but if quality or quantity certainty remains low, a collaborative environment where humans, robots and CPS work together could offer a sufficiently flexible solution (Chen et al. 2014, Wegener et al. 2014, Wegener et al. 2015). The smart factory should support more flexible production (Koren et al. 2018), reconfigurability (Koren et al. 2018)) [#2], and differentiated management and control processes (Kagermann, 2013). There is a need to support businesses in the exploration of flexible or reconfigurable factories (Maronati et al. 2018) and processing lines (ElMaraghy and ElMaraghy 2016) which have the potential to transform traditional linear value streams with well-defined interfaces and clear risks, to matrix-style operations with moving boundaries and evolving opportunities. The “moveable factory” is an interesting alternative, but currently less attractive proposition (Fox and Richardson 2017). Whatever the overall approach, lessons can be learned from the waste electrical and electronic equipment (WEEE) sector (Li et al. 2018). Here material recovery solutions involve collaborative cells (Ruggeri et al. 2017), containing vision systems and tool changing capabilities (Wegener et al. 2015), depth sensors for component locating (Bdiwi et al. 2016), socket changing (Chen et al. 2014) and mobile robots for material relocation (Minca et al. 2014). These systems (and others) require the development of suitable software (Salonitis and Stavropoulos 2013) and production chain-compliance standards (Bonnard et al. 2018, Bonnard et al. 2019) to enable autonomy via information and communications technology (ICT) integration.

The expected growth in ICT comes as no surprise considering the IoT is reliant on the internet to increase the interoperability of people and products. A high-level framework for an ICT infrastructure which is essential for the implementation of circular production systems is proposed by Asif et al. (2018) but does not explicitly consider the use of IoT, I4.0 technologies, or how remanufacturing fits. CM with its flexibility and scalability offers a route to facilitate remanufacturing (Fisher et al. 2018) but it is important to ensure good quality of

service and security, and resolve issues with network bandwidth, performance, precision and standard communication protocols (Dimitris and Ekaterini 2016). To optimise CM platforms for on-demand supply, a time-space multi-dimensional optimisation method (Huang et al. 2018) could be used. Equipment control 'as-a-service' (Adamson et al. 2016) is an interesting and applicable integrated concept that packages resources in a multi-layered CM system using intelligent decision-making modules to control and execute distributed, but cooperating, equipment [#3]. Web-based process planning in decentralised dynamic environments could also be utilised (Wang 2013) but risks to human safety in these concepts seem to be overlooked.

This section has considered I4.0 technologies in remanufacturing for the CE (summarised in Figure 5). Questions remain concerning their autonomy and cooperation (Váncza and Monostori 2017) so for these concepts to be realised, the systems will need to understand the environment in which they exist and to ensure operator safety, before accepting remotely controlled signals. Assuming the risks can be contained, and the questions resolved, real-time collaborative factories using CM systems can be expected with the integration of machine tools, robots, AM facilities etc. generating process data [#4].

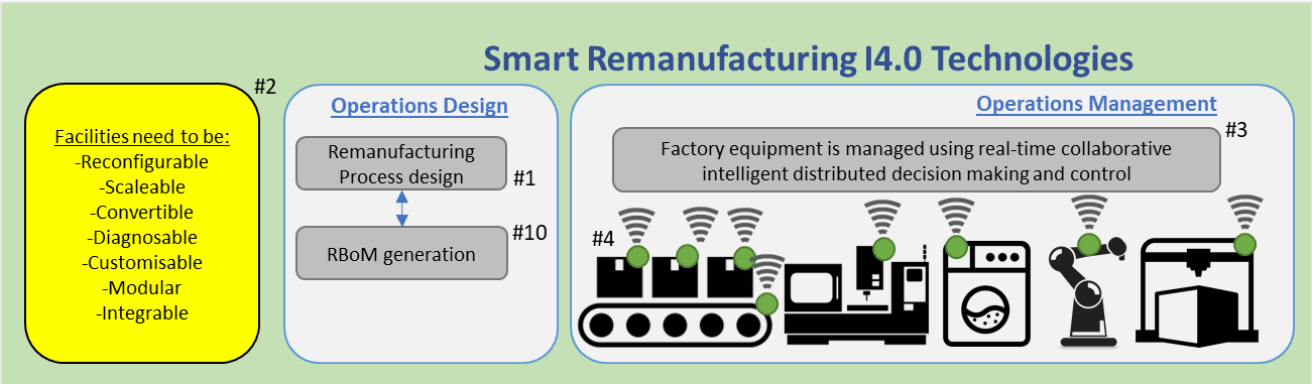

Figure 5 - Key technology-based findings

4 I4.0 for Remanufacturing against the Triple Bottom Line

Sustainable development is supported by balanced economic, social and environmental performance (United Nations 2005) which is referred to as the triple bottom line (Geissdoerfer et al. 2017). The triple bottom line is utilised in many articles to structure critical, fair and accurate appraisals. Having already covered the enabling technologies this section will expand to consider their use in remanufacturing for the CE from an economic, social and environmental perspective.

4.1 Economic Factors

Findings suggest that the social and environmental benefits of CE business models are relatively clear, but the economic elements including ownership, the cost to customer and producer, and the rebound effects of

these models, need to be further explored (Gnoni et al. 2017). For example, utilising I4.0 concepts could improve manufacturing efficiencies, making a product cheaper to purchase. However, without careful consideration of the entire life cycle, this may alter consumption rates (Raihanian Mashhadi and Behdad 2018), changing the product's remanufacturing potential. Complicating the economic assessment further, limitations have been recognised in popular Life-Cycle Analysis (LCA) techniques to describe a product at the EoL (Boks and Stevels 2007) and for meeting the needs of emerging smart supply chains. The use of real product data to generate more accurate assessments (Raihanian Mashhadi and Behdad 2018) through adapting EoL strategy tools (Cerri and Terzi 2016) or performing real-time LCA (Jensen and Remmen 2017), would be beneficial. However, the main economic themes identified from this review relate to the opportunities that exist in the relationships remanufacturing has with businesses that are transitioning to more product-service models, and how they harness the benefits of newly available product data streams.

4.1.1 Shifting Business Demands

To move towards a CE, different business models are required where manufacturers sell services to support a combination of high quality long-lasting and short-lived durable products (Esmaeilian et al. 2016). There have been several terms given to models that provision services with products (Li and Found 2017) but the most popular model identified from this review is "Product-Service-Systems" (PSS). In PSS, the supplier retains ownership of the product and leases it to the user. This prompts the owner to squeeze value out of the product for as long as it is economically viable, utilising repair and service strategies to achieve multiple life cycles, which could benefit the remanufacturing industry by providing a steady supply and demand. Remanufacturing businesses will have to adapt should their supplier or customer pursue a new PSS model as product design may be modified to assist with "servitisation" for efficient and effective service delivery. These design modifications may vary between a product intended for remanufacturing or for maintenance. This, in turn, influences remanufactured part processing, demand and opportunities. Different PSS types can enable a number of CE strategies (de Pádua Pieroni et al. 2018) and real case studies can be used to illustrate the benefits of employing digital technology in this arrangement (Bressanelli et al. 2017, Lindström 2017, Bressanelli et al. 2018). Current research into circular businesses suggest that PSS-orientated and remanufacturing-based models are particularly common archetypes (Rosa et al. 2019) yet there is a lack of large-scale quantitative studies suggesting this field is still in its infancy (Xin et al. 2017) .

Remanufacturing is a key element of circular production, promoted in scenarios where people share and lease assets (Kishita et al. 2018). Sharing or leasing will necessitate a change in manufacturing focus towards products with increased desirability, reliability, durability, serviceability, standardisation [#13] and design for disassembly, re-assembly and EoL waste minimisation. These are all made more attractive if ownership is retained and the commodity is managed using IoT technology in 'pay-per-performance' (Bressanelli et al. 2017) or 'pay-per-use' (Heiko et al. 2017) models with the product-service configuration made specific to the

business (Senzi et al. 2016), aligning with its asset recovery strategies and value proposition. Whilst there is interest in moving towards PSS business models to support sustainability, some researchers question the desire, risk and capabilities of industry to transition successfully. Currently, essential data management facilities are insufficient (Mert et al. 2016) and new methods and competences are needed to implement PSS operationally (Stark et al. 2014). However, advances in these areas are likely with rapid progress being made in the application and reliability of big data analytics and AI. More complicated to predict is whether sustainability can be achieved if the PSS model being employed is not originally designed with sustainability in mind (Pieroni et al. 2017), as PSS demand a significant shift in society and business organisation. Despite these concerns, PSS provisions are assumed to increase and are reflected in the framework alongside the traditional MoL "with customer" user state [#12].

4.1.2 Extracting Value from New Data Streams

I4.0 technologies can enable measurement capturing for factories of the future (Muñoz-Villamizar et al. 2018), with the potential to facilitate their reporting (Friedemann et al. 2016) [#14]. Traditional GDP indicators can be enhanced to include environmental, social and political elements to enable the transformation and tracking of organisations towards sustainable CE business models (Lukman et al. 2016) using I4.0 facilities. Existing critical success factors (CSF) can be useful in understanding how I4.0 works with environmentally-sustainable manufacturing (de Sousa Jabbour et al. 2018) but whatever the metrics, remanufacturing reporting will likely require product [#16], process [#17], business [#18] and logistics data [#19] to feed new internal and external decision-making systems. Captured data can be used to support purchasing and pricing, plant location, design, logistics and inventory decisions (Viet et al. 2018), all integral to the acquisition of used products (cores), the first step in the remanufacturing system (Xie et al. 2015). Without cores and a demand for products, remanufacturing is economically impracticable. Disruption and uncertainty in material supply is an issue for any business (Gaustad et al. 2017) and is particularly prevalent in remanufacturing (Guide et al. 2000). As IoT can digitally link the supplier and customer [#12] (Man and Strandhagen 2017), it may support core acquisition [#6] (Abubaker et al. 2017) with greater visibility of availability and quality. Through combining product nominal data (e.g. design specification information) [#7] with performance [#8] and product status data [#9], it may be possible to reduce risks and increase efficient resource circulation [5] (Matsuyama et al. 2015). For example, the profile of the first generation of returned cores can be used to support the planning, and provide components, for the manufacture of the second [#1]. However, linking the different generations demands smart BoM (and related Bill of Process) management. To do this, it may be possible to transform a static BoM into a remanufacturing BoM (RBoM) [#10] using the process designed by Zhou et al. (2018) that builds service BoMs for complex, variable products, representative of remanufacturing cores.

The emerging technologies discussed above are capable of facilitating the process of value co-creation and environmental sustainability along the value chain for PSS stakeholders (Li and Found 2017), strengthened by the operational data made available from CPS (Herterich et al. 2015). This data, now a commodity, can be sold to service providers including remanufacturing firms [#11] (Romero and Noran 2017). There are benefits to be had from the sharing of knowledge between producers and users. These include financial gains from longer-term relationships with the user providing access to product utilisation information for further exploitation (Wellsandt and Thoben 2016). The diversification potential of a service offering depends on the data received when the product is with the customer, either owned or leased [#12]. However, the unwillingness of users to participate in the collection of data along with the role that they play in generating and sharing it, is still a concern (Field et al. 2018). Nevertheless, if the provider remains the product owner and the partnership relies on availability (Mert et al. 2016), it will be possible to retrieve valuable information about in-use performance and surrounding influences (Abramovici et al. 2016).

This sub-section has explored the economic factors (summarised in Figure 6). The impact of I4.0 on a product's life cycle needs to be further investigated as its application may affect opportunities and profitability by changing the product's potential, likelihood and desirability to be remanufactured. The effects of I4.0 on the remanufacturing supply chain, changing product ownership and PSS are popular research topics but true economic benefits will only become evident once real-life applications have materialised. As the implementation of I4.0 is likely to be progressive and part of a continuous improvement activity, it may not be possible to assess its impact for some time.

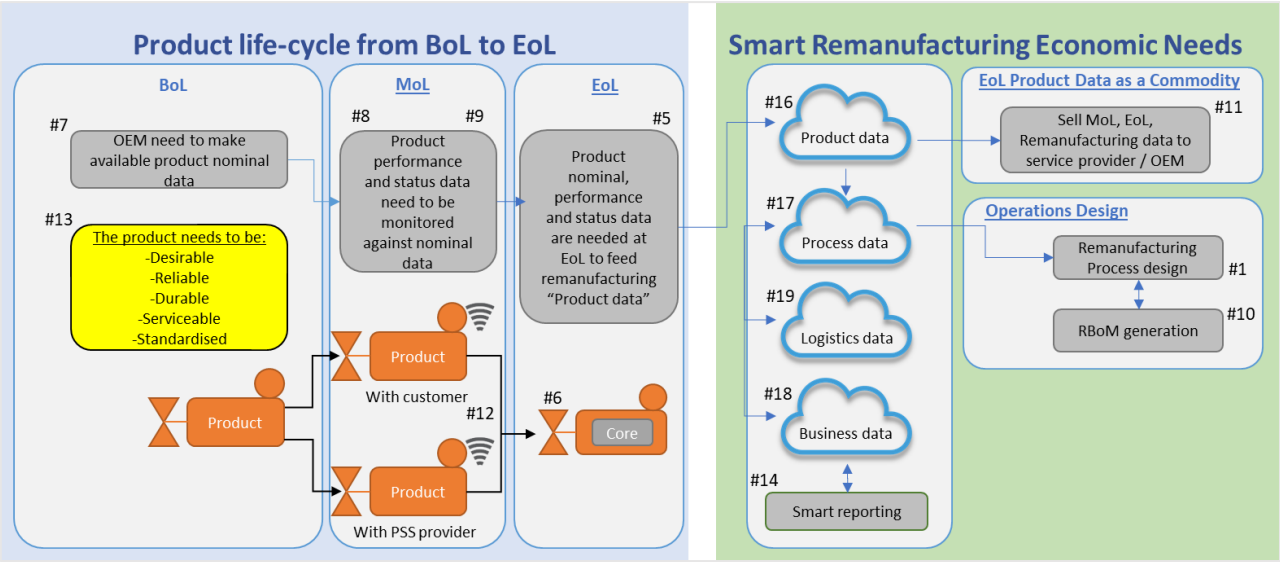

Figure 6 - Key economic findings

4.2 Social Factors

"In an increasingly complex society as well as increasingly complex manufacturing value networks, most of the challenges cannot be faced by science and technology alone" (Bueno et al. 2017). There is a need to consider human behaviours, social interactions, trends, emotions, relationships and interfaces between businesses, stakeholders and CPS. There are two emerging types of business visionaries in this area [#20]. The "ecopreneur" focuses on resolving environmental problems whilst creating economic value, whereas the "sustainable entrepreneur" resolves social and environmental problems through managing sustainable businesses (Carvalho et al. 2018). However, vision alone cannot realise I4.0, and there is a real need for a digitally skilled workforce. The lack of this is preventing investment in I4.0 technologies (Institution of Mechanical Engineers 2018) with training of engineers and operators on the benefits of CPS, and the attributes to develop and maintain them, representing one of the major barriers to adoption (Dimitris and Ekaterini 2016).

4.2.1 Workforce Capabilities

Alignment of remanufacturing skills with those required for the high-value product manufacturing sector may be advantageous as there are lower volumes and greater variability in product build specifications here, than in mass manufacture. Greater consideration needs to be given to both physical and cognitive ergonomics in factories since IoT will promote more CPS-human collaborative work environments [#21] (Siemieniuch et al. 2015). Safety will be critical, and processes will generate vast data sets, some of which will need to be human readable and understandable (Müller et al. 2018). IoT will enable autonomous decision-making in MoL in-use products that will affect EoL opportunities. However, the level of human

involvement, and the extent to which the human can override or be controlled by autonomous decisions, need to be established and customised to best suit the application and risk (Shu et al. 2017).

Managers have been identified as the most essential actors for integrating the use of I4.0 to achieve sustainability (Chauhan et al. 2019). Should they decide to exploit these technologies along with collaborative human-machine working, they would be a need to prepare employees to better understand risks and opportunities (Birkel et al. 2019) with benefits in integration and workplace enrichment expected (Stock et al. 2018). Skills transfer is not one-way with human-to-robot disassembly training also explored (Vongbunyong et al. 2017). However, most applicable articles that target training are for human operatives using I4.0 technologies including VR (Müller et al. 2016a) or AR (Müller et al. 2016b) systems, and mock products fabricated using AM techniques (Menn et al. 2017, Menn et al. 2018). VR allows users to view computer-generated 3D components, systems or environments. AR can be employed to superimpose computer-generated graphics over real-world components, systems or environments, and AM can be used to build genuine or prototype products. Early indications suggest these tools can benefit training but there are still barriers to implementation including initial equipment purchasing costs, poor portability and frequency of errors (Menn et al. 2018a). Time is likely to change this with the exposure of I4.0 technologies to engineers and operators being instrumental to understanding and developing their capabilities, which justifies their inclusion in the framework [#22].

4.2.2 Changing Societal Demands

New technologies, including VR and AR, will change the expectations of customers, partners, and employees in a continually adapting digital future (Craig 2017). Similarly, the increasing desire for customised and personalised products will impact manufacturing system design, planning and operation (Hu et al. 2011). As a result future remanufacturing systems need to be able to deal with a higher level of variety, best managed when a product is first designed with it in mind (Kuo and Smith 2018). A key area of research in need of exploration is the connection between business models and design-for-remanufacturing strategies (Esmaeilian et al. 2016). Whilst there is no work identified from this search that explores this connection, applicable Design-for-Disassembly (DfD), Design-for-Service (DfS), Design-for-Sustainability (D4S) and DfR strategies have been summarised (Chang et al. 2017a). Adopting smart interface design concepts with tools to evaluate adaptability (Gu et al. 2004), or open-architecture products, modular in structure allowing design input from the end user (Koren et al. 2013) could help engineers future-proof and prepare EoL strategies for remanufacturing. “Designing-in” extension to product life cycle features, and improving the predictability of upgrade windows and EoL product retirement is a feasible approach (Erler and Rieger 2016). These considerations at BoL have implications on the ease and profitability of remanufacturing [#23].

Whatever the business approach, companies who engage in advanced manufacturing practices at the operations level do not necessarily participate in environmental management at the tactical or strategic levels (Muñoz-Villamizar et al. 2018). However, this statement is based on one article that focuses only on Small-Medium Enterprises (SMEs) in Spain. Notably, much of the research in this area is undertaken in developed countries. The relationships between the different business levels in SMEs to large corporations around the world should be further explored (Müller and Voigt 2018). On this, several articles highlight that there are numerous and complex economic and social challenges in the implementation of sustainable strategies in developing or newly industrialised countries (Singhal et al. 2018, Szalavetz 2018, Wakjira et al. 2018). A key trend in these papers is the recognition that literacy and general awareness of sustainability are barriers to implementation (Ibrahim 2017). It is therefore necessary to consider the impact of global cultural differences on remanufacturing as more of the world becomes technologically advanced.

This sub-section has considered the social factors (summarised in Figure 7). The social impacts of I4.0 in remanufacturing are much the same as in other IoT application areas (e.g. Energy and Healthcare) where the skills, attributes and behaviours of the humans involved will change. Some of the emerging technologies can be utilised in training and design to encourage consideration of a product's EoL at the BoL stage, but people must first recognise the importance of sustainability and the benefits of IoT to make progress. Furthermore, ideas spawned in developed countries need to suit conditions in those still developing, as the I4.0 infrastructure of the future is global. The proposed framework contains reference to VR and AR in training, and sustainable manufacturing and entrepreneurship as an attribute of the I4.0 remanufacturing workforce.

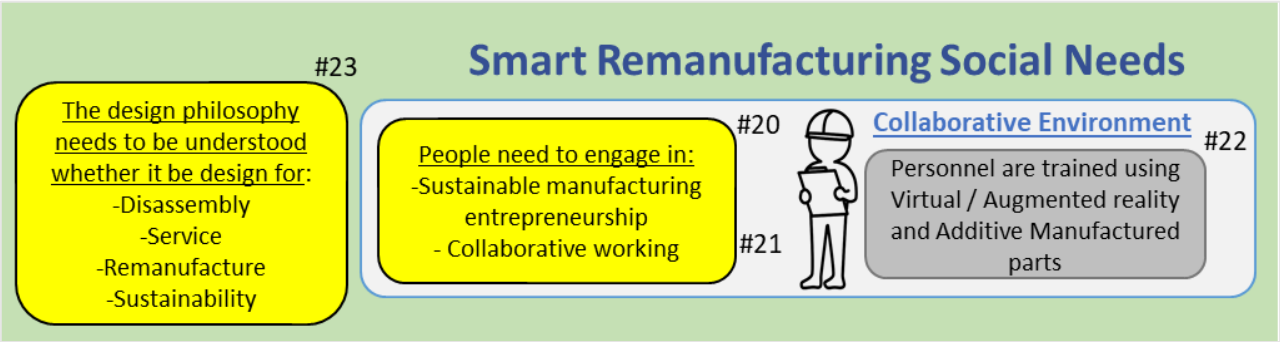

Figure 7 - Key social findings

4.3 Environmental Factors

There were few articles related to this section, yet their quality and contribution were significant. "Nature has been and is supplying the necessary resources for men and technology's life cycles as well as absorbing and metabolizing related waste" (Jovane et al. 2017). Whilst, I4.0 can permit the efficient allocation of resources using real-time data from production systems and the supply chain (de Sousa Jabbour et al. 2018), its ability to bring habitual sustainable manufacturing practices to fruition is highly dependent on the

digitalisation of existing technologies (Carvalho et al. 2018). However, I4.0 alone does not explicitly tackle sustainability in manufacturing (Man and Strandhagen 2017) so regulations and standards are being used to drive it.

4.3.1 Regulations and Standards

Directive 2009/125/EC (European Council 2009) establishes a framework for the setting of standards for nations to structure policies to encourage manufacturers to consider a product's environmental life-cycle impact at the design stage. At this stage, there is the greatest opportunity to facilitate efficient use of resources integrating the requirements into CE marking and the declaration of conformity certification process. BS ISO 8887-1:2017 (British Standards Institution 2017) specifies requirements for the content and structure of technical documentation at the design stage as compulsory output deliverables to include information on manufacturing and EoL processing of products through potentially multiple life cycles focusing on minimising environmental impact. It also demands the archiving of information on assembly methods and batch sizes, test certificates and results, previous life cycles and EoL decisions. These standards will influence the remanufacturing industry [#24], customer attitudes towards remanufactured components, information availability and product remanufacturability, all of which contribute to changes in consumption.

4.3.2 Green Demands

Boks and Stevels (2007) stress that general principles have little value unless made specific to the context in which they will be used. In their thought-provoking article, they evaluate the impact of green principles using real examples and suggest the perception of what is green depends on the values that different stakeholders hold. Rethinking a product as a dynamic evolving set of characteristics or qualities, rather than static entities, could create new opportunities [#26]. As companies utilise the I4.0 technologies to gather MoL data, they can better understand usage patterns and configure offerings to suit different customers in a much finer-grained fashion (Spring and Araujo 2017). With this new dynamic set of characteristics, the way that products are identified and valued may change. 'New' and 'remanufactured' products may not be differentiated if they meet the users expectation and the specified functionality (Tolio et al. 2017) [#27]. With this, the smart circular factory could perform manufacturing and remanufacturing operations, smoothing product variability, with minimal environmental load. However, the product is not the only consumer of natural resources in the remanufacturing supply chain. The factories themselves also need to be considered. Monitoring factory assets to reduce resource consumption (Peralta Álvarez et al. 2017) and using lighter weight AM components for products or remanufacturing equipment can cut emissions (Abdulrahman et al. 2018) and thus the impact of the remanufacturing business on the environment. Looking further afield, Byrne et al. (2018) present an interesting paper that reviews biologicalisation and provides recommendations on the integration of biology or biologically inspired concepts into applicable methods and models, CPS, digitalisation and I4.0 [#25]. Exploring nature and the relationships between

science, technology and sustainability, Healy (1995) warn of the over reliance of technology to resolve issues in the environment that have themselves been caused by technology. He proposes a realignment of science, technology and politics with the idea of being 'in' instead of 'managing' nature and presents 'metascience' as a more flexible all-encompassing subject over 'black-boxed' engineering that currently encourages boundaries, assumptions and a narrowing of vision, and therefore ignores external implications.

This sub-section has collated the findings related to environmental factors. Research in the area is fragmented but interesting. Little work is being conducted on the subject and what has been undertaken is either bundled under the general manufacturing umbrella or touched on at such a high level that it is ambiguous. However, there is widespread recognition that the depletion of the earth's natural resources must stop, and many researchers state that deploying I4.0 and IoT technologies in remanufacturing could be environmentally helpful. Standards aimed at the manufacturing industry can apply in part, so too the concepts of biologicalisation, the perception of "green" and the acceptance of remanufactured parts back into the supply chain. These have been included as overriding factors in the research framework as real focus on the environmental impacts of I4.0 on the remanufacturing field is lacking.

5 Framework and Agenda for I4.0 in Remanufacturing

As mentioned in Section 2.1, 329 articles from a systematic database search were identified as being relevant to I4.0 in remanufacturing for the CE. Most of the technologies within remanufacturing already exist within the manufacturing space but a gap was identified in the literature on smart technologies for the CE specifically in remanufacturing. To fill this gap, a review has been conducted to describes current trends before looking at how I4.0 for remanufacturing can influence or be influenced by economics, society and the environment. The key findings, referenced throughout this article as [#X], are listed in Table 1 together with other conclusions as research hypotheses. They contribute to the development of Figure 8 which presents a framework for I4.0 in remanufacturing for the CE (arrows represent the flow of the physical product or associated data in a smart remanufacturing environment and the yellow boxes represent key enablers). Section 5.2 then sets out the research agenda. The framework should provide industry with a vision of the smart remanufacturing future, whist the agenda should offer scholars a summary of the major topics and potential research directions.

5.1 Framework

At BoL, the product needs to be designed with the most applicable philosophy whether it be DfD or DfR, etc. [#23]. It should be durable and serviceable to extend its life expectancy, but also standardised to support automated EoL processing [#13]. Product nominal data [#7], made available at BoL, should feed into MoL data, influencing both MoL performance [#8] and status data [#9], all useful to future product design [#31]

and service provisioning (internal or external) [#28]. The data stream ends up as EoL data [#5], available to sell as a commodity [#11]. Whilst with the customer (potentially leased from a PSS provider [#12]), the product should be connected to the IoT, supplying MoL data such as operating and environmental parameters. Gaps in data should be filled utilising AI techniques to provide transparency and comparability of product condition, remaining life and failure trends [#29]. This big data can be extrapolated to support remanufacturing process management but the effect of poor or incomplete data on subsequent decision-making and throughput needs to be appreciated (Okorie et al. 2018a).

The nature of remanufacturing products with variable quality calls for a flexible, potentially cyclic revision of process redesign [#1, #10] dependent on core attributes and desired outcome (complete, partial, targeted or destructive disassembly etc.) [#6]. Using AI to plan, schedule and optimise, remanufacturing process design [#30] can influence, and be influenced by, decisions made in the logistics data space, where AI supports management of resources and pricing takes place in a cloud-based system [#15, #19]. The product's unique ID [#16] is utilised throughout remanufacturing to interface with the BoL-EoL data streams and to track remanufacturing progress [#17].

Process design distributes intelligent decision-making on the operations that can / need to be completed. These cover the allocation of resources, potentially across multiple facilities [#33], and the tracking of progress in real-time against the schedule to optimise profitability [#18]. Networked machines, CPS, robots and products provide real-time operational data for reporting metrics, in reconfigurable, modular factory environments [#3]. Product [#16], process [#17] and business data [#18] are managed using CM methods that are scaleable, providing sufficient bandwidth, performance and security [#32]. (There are general requirements to define data structures and compatibility, security, scalability and resource consumption of IoT technology throughout the value network, to use big data, machine learning and AI. However, these are not unique to remanufacturing and will likely affect other sectors more (e.g. healthcare or banking) forcing the development of suitable transferable solutions.) AI systems fill voids in product and operational information and consider the data obtained during MoL to observe patterns in customer behaviours relating to product condition [#29].

Flexible, reconfigurable facilities [#2] are supported by operators, maintenance technicians and engineering teams that are trained in CPS [#22], human-machine interoperability [#21] and sustainable manufacturing methodologies [#20] facilitated by I4.0 technologies [#4]. Business metrics are reported using new CSF [#14], lessons learned can be shared with OEMs, and closer relationships can be formed between the user, customer, PSS provider and remanufacturer.

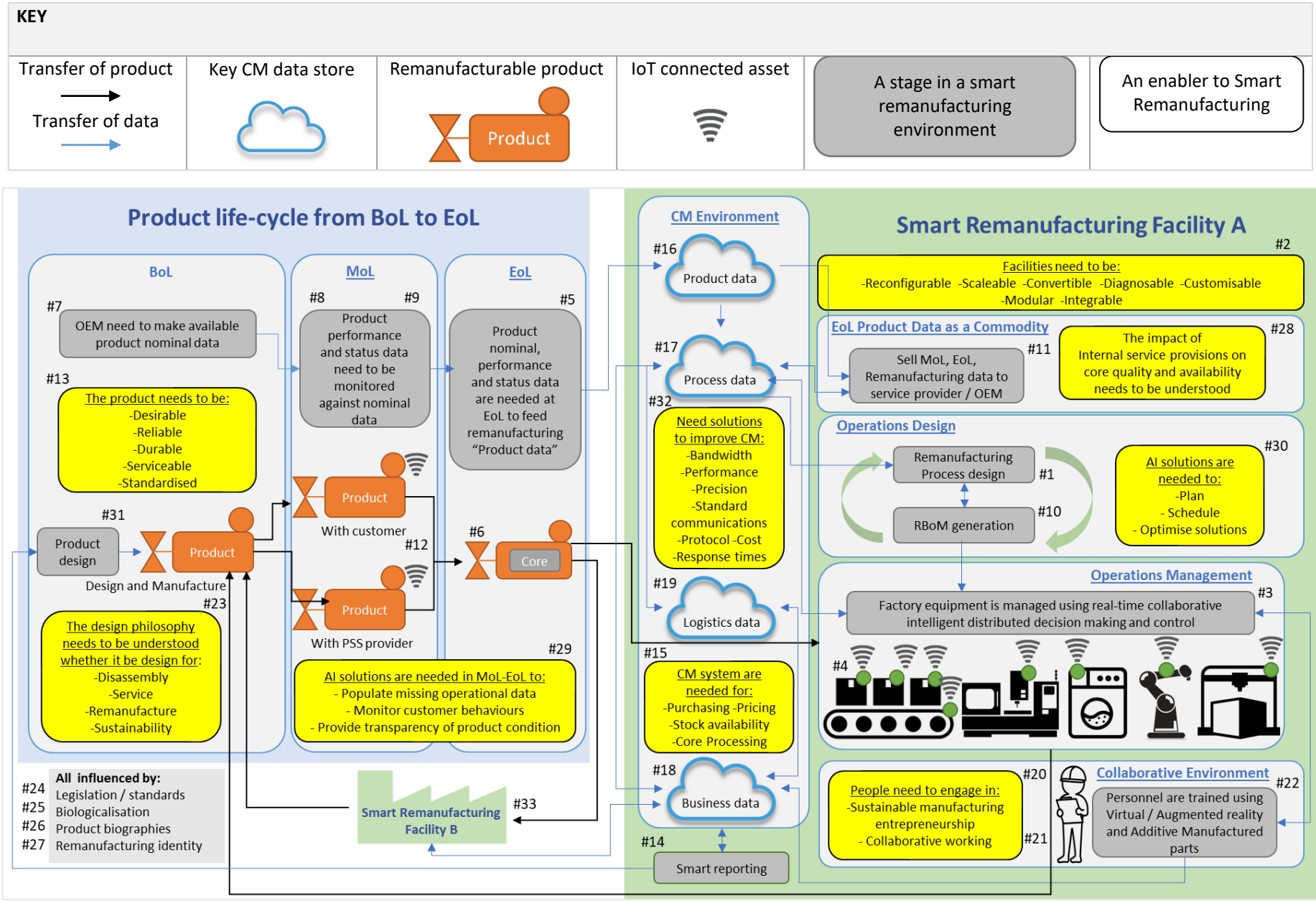

Figure 8 - Proposed framework for I4.0 in remanufacturing for the CE

Table 2 – Research Hypotheses

#	Review findings as hypotheses for Smart Remanufacturing research
1	Smart remanufacturing process design uses logistics data, discrete event simulation, with real-time AI planning, control and decision-making tools.
2	Characteristics of a smart reconfigurable remanufacturing system include scalability, convertibility, diagnosability, customisation, modularity and integrability.
3	A smart remanufacturing facility utilises intelligent and distributed decision-making modules to control and execute distributed, but cooperating, shop-floor equipment.
4	Web-based distributed process planning in a decentralised dynamic environment supports real-time collaborative factories using CM systems.
5	The product at EoL (with customer or PSS) provides the core for remanufacturing and the information for EoL processing.
6	The IoT is used to support core acquisition and inform and trigger reverse logistics activities.
7	BoL product nominal data provide information on the original design and manufacturing parameters.
8	MoL product performance data provide information on the quality of the product and its service history.
9	MoL product status data provide information on life expectancy.
10	Linking the EoL of one product generation to the production of the next generation demands smart BoM management and is dependent on smart remanufacturing process design.
11	CPSs provide a product's MoL data to sell as a commodity to service providers including remanufacturers.
12	MoL data can enhance the knowledge shared between producers and users when the product is with the customer, either owned or leased.
13	Product sharing or leasing necessitates a change in manufacturing focus towards products with increased desirability, reliability, durability, serviceability and standardisation.
14	I4.0 technologies are enablers of measurement capturing and reporting in smart remanufacturing.
15	In smart remanufacturing, data are used to support supply chain inventory decisions, plant location and design, logistics, purchasing and pricing.
16	Smart remanufacturing reporting requires product data managed using CM methods supplied at EoL.
17	Smart remanufacturing reporting requires process data, relevant to the process design, managed using CM methods.
18	Smart remanufacturing reporting requires business data managed using CM methods.
19	Smart remanufacturing reporting requires logistics data managed using CM methods.
20	Environmentally conscious business visionaries and managers facilitate sustainable remanufacturing.
21	Physical and cognitive ergonomics must be considered as IoT will promote greater CPS-human collaborative work environments.
22	The exposure of engineers and operators to I4.0 technologies promotes their application.
23	The design philosophy adopted at BoL influences ease of EoL disassembly, remanufacturability and profit margins.
24	Legislation and standards applied to the product to be remanufactured or the remanufacturing industry directly impact resource consumption.
25	Nature-inspired concepts can be integrated with CPS, digitalisation and I4.0 technologies in smart remanufacturing.
26	The IoT can be used to build product 'biographies', opening up new business opportunities arising from owning, controlling and integrating the generated data streams.
27	New products and remanufactured products are not differentiated if they meet the customer's expectation and the specified functionality.
28	Internal and external services make use of MoL data that provide information on core availability and remanufacturing opportunities.
29	During MoL, products are connected to the IoT, with AI techniques employed to fill gaps in data and to provide transparency and comparability of product condition, remaining life and failure trends.
30	AI techniques are used in planning, scheduling and optimising remanufacturing process design which influences, and is influenced by, decisions made in the logistics data space.
31	The availability of BoL from the OEM, MoL data from the connected product and EoL data from remanufacturing helps future product design.
32	CM methods that are scaleable, with suitable bandwidth, performance and security benefit the variable resource consumption associated with remanufacturing.
33	Distributed intelligent decision-making is utilised for the allocation of resources, across multiple facilities, and the tracking of progress in real-time against the schedule to optimise profitability.

5.2 Research Agenda

From the framework some key recommendations for further work can be proposed. For researchers, the main themes are identified in Table 3. When pursuing any of these suggestions, scholars must remain conscious of the need to ensure future remanufacturing aligns with CE and sustainable development principles. For industry-base readers, the framework could be used to identify a process to trial the implementation of I4.0 technologies. This will support workforce development and provide a real environment to explore capabilities, interfaces and benefits.

Table 3 - Research Agenda for Smart Remanufacturing

	Brief Definition	Research Agenda	
Technology	Smart remanufacturing assumes the utilisation of I4.0 technologies on the product to be remanufactured as well as the remanufacturing processing equipment and business management systems.	Product	a) Investigate the remanufacturing functions that are affected by product quantity and quality that could benefit from data supplied by I4.0 technologies b) Evaluate the sustainable benefits of the technology on these functions using real world applications c) Identify the data requirements from existing products to enable intelligent future life-cycle decision-making
		Process	a) Explore the integration of I4.0 technologies to develop flexibly managed remanufacturing process b) Develop AI decision-making solutions to support remanufacturing planning, control and execution c) Evaluate factory digital twins for simulating potential process outcomes based on inbound product knowledge
		Management	a) Explore how autonomous decision-making in MoL in-use products could generate/influence EoL remanufacturing opportunities b) Analyse management metrics and evaluate benefits of real-time data input c) Identify, invest and support the technical team implement I4.0 technologies in processes that they already understand to encourage the exploration of I4.0 in real applications
Economic	Engagement with both traditional and PSS business models will be needed simultaneously whilst the emergence of new data streams will offer alternative / more efficient value streams.		a) Investigate and analyse mechanisms to facilitate the optimisation of remanufacturing businesses within, or alongside PSS structures b) Identify key remanufacturing business metrics that can be enhanced with near real-time data input c) Explore the economic benefit of investing in systems that can extract historical or MoL data from products to sell back to the OEM
Social	Smart remanufacturing systems will be developed and maintained by specialists in CPS, HMC with an appreciation of evolving global cultural differences and challenges.		a) Investigate the skillsets of workers in the high-value product manufacturing sector for cross referencing with the manufacturing sector b) Demonstrate more HMC/HRC and flexible facilities on real remanufacturing case studies c) Inquire into the psychology of society to accept 'new' and 'remanufactured' products as equal
Environmental	The smart remanufacturing industry can influence and be affected by government policies aimed at sustainable development.		a) Explore environmental implications of hybrid materials and structures on remanufacturing processes b) Further consider the integration of nature inspired concepts into applicable smart remanufacturing methods and models

This work does have limitations and can be further developed. The initial article search used specific keywords in English that could be adapted or expanded. The framework could be presented to stakeholders and/or interrogated further. Real case-studies from developed and developing countries could be overlaid to explore trends, gaps and social challenges. However, the next steps should include the exploration of the themes in

Table 3 along with the development of a strategic time-based roadmap specific to a remanufacturing business to encourage adoption from quantitative, real-world studies prioritised accordingly.

6 Concluding Remarks

The contribution of this article is twofold. First, it presents the findings of a systematic review covering literature to August 2019 with respect to the triple bottom line. Second, it builds a framework and research agenda from the findings, identifying relationships and gaps that can be explored in the future.

There are many frameworks that encourage discussions on I4.0 in manufacturing, with far fewer in remanufacturing. Those frameworks addressing remanufacturing present a vision of new business models, an increase in PSS structures, greater automation with digitalised links between customers and suppliers and a change in skill sets. As remanufacturing relies on suppliers for cores and customers for sales, remanufacturers will also need to adapt and digitalise to remain competitive.

Future work needs to be aimed at developing, and demonstrating, in real remanufacturing applications, the relationships and interfaces, methods and protocols that link the key findings. The impact on changing remanufactured product ownership should be explored as this may influence the service and support structure of stakeholder organisations. The expansion of PSS encourages the exploitation of MoL data to provide users with enhanced support, service and EoL decision-making. PSS may drive OEMs to consider D4S, which will impact remanufacturability depending on their approach (to support maintenance, service, remanufacturing or disposal etc.). How these models affect remanufacturing remains to be seen. However, what is evident is that there are opportunities to use the MoL data to understand failure modes and extrapolate life expectancy (Ondemir and Gupta 2014). This is potentially useful information to remanufacturers should they be able to adapt their processes accordingly to take full advantage of the data. This concept should be further explored as there is currently little evidence to suggest that remanufacturers would change their processes based on the availability of MoL information alone.

Business models will need to be adapted to consider an increase in robotics, automation, CPS and the integration of ICT with big data analytics, machine learning, AI and decision-making capability. These technologies will affect both manufacturing and remanufacturing in the short term. At the shop-floor level, the use of I4.0 technologies could allow for greater product and process information availability, but the accuracy, timeliness, and completeness of the data need to be managed appropriately. New measurements and critical success factors are likely to be required to track progression towards sustainability that may or may not align with those developed for manufacturing. At the same time, the adoption of synthetic biology-based processes and the diffusion of capabilities enabling the creation of advanced materials (Roos 2016), represent potential medium to long-term developments.

I4.0 will bring the end-to-end value chain stakeholders closer together, with IoT transforming their relationships from a linear to a networked multi-level one, and remanufacturing businesses will have to respond to this. Flexibility is key, with the concept of reconfigurable remanufacturing CPS utilising cloud-based IT systems providing a vision of the future.

Funding

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

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