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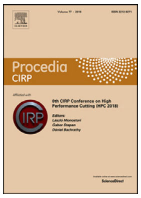

Recycling 4.0 – Mapping smart manufacturing solutions to remanufacturing and recycling operations

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ABSTRACT

Anthropogenic environmental impacts can largely be attributed to manufacturing. Two paradigms are promising solutions to mitigate the consequences of manufacturing: Industry 4.0 (smart manufacturing solutions) through increased efficiencies and Circular Economy (CE) through remanufacturing and recycling and avoiding manufacturing of new products. Potentials and challenges from combining the paradigms and thus, from transferring Industry 4.0 to remanufacturing and recycling operations need to be analyzed. This paper identifies smart manufacturing technologies and solutions, which support CE and maps them on remanufacturing and recycling operations to derive a Recycling 4.0 framework.

1. Introduction

Through manufacturing, our societies create the products they desire. The process transforms renewable and non-renewable materials, consumes substantial amounts of energy, and releases emissions into the environment, which impact air, water and soil. The demand for products is growing due to a rising global population, increasing standards of affluence, and fueled by the way of consumption in ‘throwaway’ societies (Gutowski et al., 2013, Duflou et al., 2012). Therefore, it is widely accepted by politics, research and companies, that future manufacturing has to decrease its environmental impact. Goodland (Goodland, 1995) defined this as seeking to “… improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans”. Recently, this has led to a stronger definition of sustainability by nesting the social dimension and with it the economic dimension into the environmental dimension of sustainability (Rockström, 2015). Two current paradigms promise improved environmental sustainability for manufacturing: Industry 4.0 (I4.0), also known as smart manufacturing, and Circular Economy (CE). Both support mitigating process inefficiencies e.g. by gathering, processing and sharing relevant data within companies, supply chains or along product life cycles. An advantage of CE is that recycled or remanufactured secondary materials and components with a lower environmental impact can substitute newly manufactured materials and products (Allwood et al., 2011).

It is uncertain which potentials and challenges might result from combining the two paradigms. Therefore, the aim of this paper is to propose a framework for recycling 4.0, which allows for linking smart manufacturing solutions and remanufacturing and recycling operations. The paper is structured as follows: Section 2 introduces the underlying paradigms I4.0 and CE and includes a literature review on the combination of both. Based on this, Section 3 presents the proposed framework approach for evaluating the suitability of I4.0 technologies and solutions to support CE operations. In Section 4, this framework is applied to a case study regarding the recycling of Li-Ion batteries for electric vehicles (EVs). Finally, Section 5 provides a summary and an outlook.

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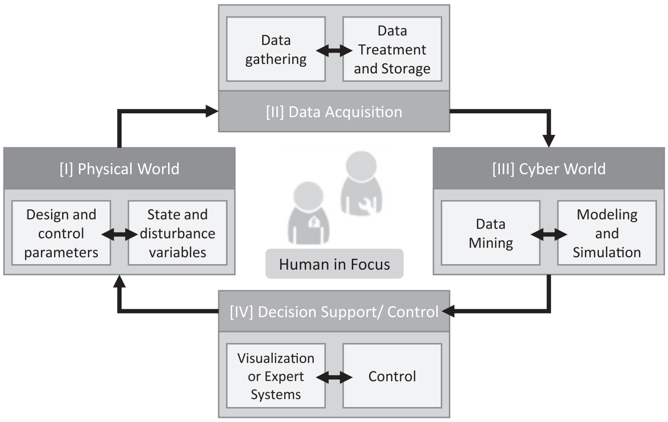

Fig. 1. CPS framework with subsystems (adapted from Thiede et al., 2016).

2. State of research

2.1. Industry 4.0

One technical centerpiece of I4.0 and smart manufacturing are cyber physical systems (CPS). Generally, CPS “are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-providing services” (Kang et al., 2016). Within industrial settings, CPS are applied to incorporate new, designated functionalities by utilizing existing IT infrastructure, but also additional hardware such as sensors. Based on the general definition of CPS, Fig. 1 shows a framework with four subsystems (I-IV) and comprising elements. This framework may be applied to single processes and machines but also to complex (re-)manufacturing systems as a whole.

CPS consist of a physical (I) and a cyber (III) world interconnected by data acquisition (II) and decision support resp. control (IV) functionalities. The physical world (I) includes the actual physical equipment (machines transportation systems, technical building services). The state of the physical world is influenced by various internal and external factors. To represent the subsystems state, these factors can be measured with data acquisition (II) infrastructure. Temporal and spatial resolution of the measurements, as well as suitable data treatment and storage structures are dependent on the specific use case. Within the cyber world (III), data mining and/or simulation methods can be applied to those data flows, e.g. to analyze and predict the behavior of the physical infrastructure. This information may be used for decision support (IV) or directly embedded within automated control (IV) of technical systems. This serves to close the information loop and directly influence the considered physical object through its design and control parameters. Human operators should always stay in focus at least through appropriate visualization of the systems status. The information exchange between all subsystems and elements is ensured by a diversity of connecting interfaces (e.g. network devices, protocols) (Thiede, 2018).

2.2. Circular economy

The basis of the Circular Economy (CE) paradigm are different of end-of-life management options, which cascade either complete products, or parts and materials into additional life cycles (Fig. 2).

The aim is the organization, engineering and control of activities, which enable the conservation of the economic and ecological value of unwanted or unsuitable (End-of-Use, EoU), and degraded or inoperable (End-of-Life, EoL) products (Herrmann, 2010). Examples include the refurbishing or remanufacturing of products and parts (Steinhilper and Weiland, 2015), or the recycling of materials, e.g. plastic waste or Li-Ion batteries (Cerdas et al., 2018).

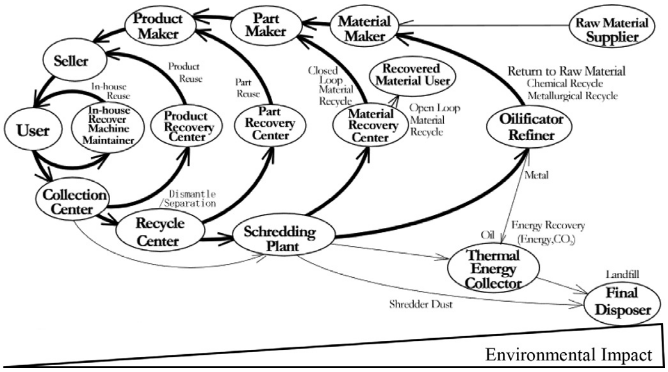

Fig. 2. Comet circle as proposed by Ricoh Co. Ltd. (adapted from Tani, 1999).

The cascading options have the potential to mitigate environmental consequences related with product manufacturing: By avoiding harmful waste disposal practices like landfilling (packaging waste); and by decreasing the demand for primary materials by providing secondary materials with a lower environmental impact (Geyer et al., 2016; Ashby, 2013).

2.3. Industry 4.0 and circular economy in combination

Research regarding I4.0 in combination with CE has been increasing recently and a brief overview of literature is given in the following. Kerin and Pham (Kerin and Pham, 2019) claim that technologies such as Internet of Things (IoT), Additive Manufacturing, collaborative robots (cobots), Virtual/ Augmented Reality (VR/AR), and data carrier technologies like RFID are promising for the remanufacturing sector. Mainly because operations in this sector still consist mostly of manual processes. Yang and colleagues (Yang et al., 2018) discuss challenges and opportunities of smart solutions in the remanufacturing sector; challenges include a lack of standardization, life cycle design and a limited information exchange. Opportunities are increased efficiency and reliability of remanufacturing processes via I4.0 ‘smart factories’, as well as technologies such as additive and hybrid manufacturing, 3D scanning, Automated Transport Systems (ATS) and AR to decrease costs and increase quality of remanufactured products. Lopes de Sousa Jabbour et al. [17] present a case study, in which a smart and flexible (re)manufacturing system can choose the most efficient processes out of a number of available EoU/EoL processes to minimize effort, based on provided product information (i.e. a ‘product passport’). Further publications analyze the challenges and potentials of specific I4.0 technologies for sustainable (re-)manufacturing and recycling (Yi and Park, 2015; Stock and Seliger, 2016; Wang and Wang, 2019, Gartner Inc. 2018); Finally Thiede (2018) discusses the environmental feasibility of CPS by analyzing both, expected environmental benefits, but also related environmental impacts of a CPS implementation for the example of continuous energy monitoring. Unfortunately, these publications do not incorporate a general evaluation of I4.0 and CE in combination with each other and in relation to remanufacturing and recycling. Therefore, no structured decision support to select existing smart solutions for remanufacturing and recycling operations is available.

3. Materials and method

To map existing I4.0 technologies and solutions onto remanufacturing and recycling a 3 step methodology is proposed.

Table 1
Identified I4.0 technologies and smart solutions.

CPS element	Technology description
Data gathering (II)	Sensors gather product (e.g. health status, energy usage) and product-related data (external influencing factors, e.g. ambient temperature) (Thiede et al., 2019). Smart products, which collect, save and share data from their life cycle phases, imply the need for data acquisition.
Data treatment and storage (II)	Product-based information carrier technologies like RFID or QR codes store product information. Tracking products and supplying relevant product data in reverse logistics and (re-)production scheduling offer high potential for remanufacturing and recycling (Kerin and Pham, 2019; Lopes de Sousa Jabbour et al., 2018).
Data mining (III)	Data mining is part of the process of knowledge discovery from databases (KDD) and can be defined as “the nontrivial process of identifying valid, novel, potentially useful and ultimately understandable patterns in data” (Fayyad et al., 1996)
Modeling and simulation (III)	For example, the digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a product, that mirrors the status and behaviour of its real world twin. Through the entire product life cycle it provides and forecasts information such as damage and life prediction for improved management (Wang and Wang, 2019).
Visualization (IV)	For example, Virtual (VR) and Augmented Reality (AR) are technologies for human decision support. AR is proposed for training and supporting processes in logistics or maintenance (Kerin and Pham, 2019). For the remanufacturing and recycling sector, AR has a high potential for supporting workers, i.e. at (dis)assembly processes with manual instructions due to the high variety of products.
Control (IV)	Controlling machines/systems can be achieved by traditional technologies like Computer Numerical Control (CNC), innovative technologies like deep learning (Thiede et al., 2019) or via haptic feedback, e.g. for cobots.
Solution description	
Smart bin	The smart bin is an IoT solution for collecting and sorting used products; it can recognize and sort recyclables automatically by artificial intelligence-based object recognition. Further, it can check its fill level for efficient route planning in reverse logistics (Folianto et al., 2015).
Automated Transport System (ATS)	For example, Autonomous Guided Vehicles (AGVs) navigate autonomously through the shop floor for intracompany transport tasks (Yang et al., 2018).
‘Pick by vision’ (PBV)	PBV combines (optical) real-time sensors and visualization approaches to capture the real world and support decision making by providing additional visual information (Reif and Günthner, 2009). This solution has potential regarding manual (dis)assembly and sorting processes.
Collaborative robots / Cobots	Cobots combine sensing and real time adaption (Ruggeri et al., 2017) for direct physical interaction between a human worker and general purpose manipulators in confined spaces without endangering employees. Cobots can support workers in the (dis)assembly processes of heavy and heterogeneous product streams as they can deal with the variability regarding products, quantity and quality (Kerin and Pham, 2019).

Table 2
Typical remanufacturing and recycling operations.

	Collection	Identification / Classification	Fault detection	Disassembly	Repair	Assembly	Function check	Material separation	Sorting
Remanufacturing	X	(X)	X	X	X	X	X	-	-
Recycling	X	X	-	(X)	-	-	-	X	X
X necessary operation		(X) optional operation				- not needed operation			

3.1. Step 1: Identifying industry 4.0 / smart solutions

For the identification of promising technologies and solutions for the remanufacturing and recycling sector, the CPS framework (Fig. 1) is used to distinguish between technologies and solutions as well as to classify relevant literature. Smart manufacturing technologies refer to the single elements of the CPS framework. Smart manufacturing solutions, are approaches, which incorporate all comprising elements (technologies) of the framework. If a technology is employable within the framework, it was taken under consideration; the same applies to complete ‘smart solutions’, which already incorporate all of the framework’s elements. A selective classification of the identified I4.0 technologies and solutions is given in Table 1. The selection is based on expert and project-related knowledge which serves as a basis for the identification of most promising technologies and solutions for the EoU/EoL sector.

3.2. Step 2: Identifying remanufacturing and recycling operations

Operations for remanufacturing and recycling process chains are listed in Table 2. EoU/EoL treatment usually starts with the collection and transportation of used products to the Original Equipment Manufacturer (OEM) or remanufacturing/ recycling plant, creating a need of data (e.g. product location, quantity and quality) for the management of reverse supply chains. Treatment requires a classification step to gain knowledge of the product type, used materials and overall status e.g. for deciding whether an EoU/EoL product is worth remanufacturing or to know the optimal disassembly order.

Within remanufacturing, fault detection is necessary to identify broken components. The goal is a failure detection without the need of disassembling the complete product to repair or exchange the erroneous components. After the repair operation, the product is reassembled and a final functionality check is done. Material separation and sorting are typical recycling operations aiming to break up the material cohesion and to sort the materials into homogenous material streams to supply new raw material. Both process chains benefit from information exchange between OEMs and recyclers to provide recycling-relevant product information. A Design for Remanufacturing/Recycling (DfR) with nondestructive and easy dismantling options plays an equally important role (Ferrão and Amaral, 2006).

3.3. Step 3: Mapping smart solutions to remanufacturing and recycling operations

Table 3 shows the results of the mapping. The vertical axis is divided between the CPS technologies and complete I4.0 solutions. The individual potentials are differentiated by *no effect of I4.0 integration* (“0”) and *expected positive influence of I4.0 integration* (low “+”, high “++”, very high “+++”). A positive influence means, that

Table 3
General mapping of smart technologies and solutions to remanufacturing and recycling operations.

	Collection	Identification / Classification	Fault detection	Disassembly	Repair	Assembly	Function check	Material separa.	Sorting
Technology									
Data gathering (II)	+++	+++	+++	++	++	+	+	+	+++
Data treatment & storage (II)	+++	+++	+++	++	++	+	++	+	+++
Data mining (III)	+++	+++	+++	+	++	+	+++	++	++
Modeling & simulation (III)	+	+++	+++	+++	+++	+++	+++	++	++
Visualization (IV)	++	+++	++	+++	+++	+++	+	+	++
Control (IV)	++	++	++	+++	++	+++	++	+++	+++
Solution									
Smart bin	+++	+++	0	0	0	0	0	++	+++
ATS	+++	+	0	++	+	++	0	0	0
PBV	+	+++	0	+++	++	+++	0	++	++
Cobots	+	++	0	+++	++	+++	0	++	0

I4.0 integration can improve the environmental or economic performance of an operation.

3.4. Interpretation of mapping results

As shown in Table 3 no technology or solution is expected to have a high positive impact for all EoU/EoL processes.

Data gathering, treatment and storage, and mining are expected to be particularly suitable for collection, identification/ classification, fault detection and sorting processes, if these three technologies are deployed together. Data mining is also expected to be helpful for automated function checks at the end of a remanufacturing process chain.

Modeling and simulation is expected to have great potential for testing and predicting the behavior of complex systems: for predicting faults, testing repair strategies or checking the functionality during remanufacturing, or for testing and improving (semi-)automated systems like (dis-)assembly systems.

Visualization, e.g. by VR or AR, has great potential for manually intensive processes like (dis-)assembly or repair; but also to support product identification/ classification.

Control technologies are expected to have a positive impact on those processes, which could potentially be or already are automated, such as (dis-)assembly or material separation. Smart bins are useful for collecting, classifying and sorting EoU/EoL products; for further processes, this solution has no direct impact and its contribution may be to connect the product use phase and the final EoL treatment.

ATS show low potential for supporting recycling, as the process chain often incorporates shredding or material separation and transportation is provided by conveyor belts. Nevertheless, ATS may be useful for the remanufacturing of heavy products that run through different processes at different locations.

As PBV focuses on visualizing the information for workers, it addresses similar processes as AR. PBV focusses more on the classification of components after the (dis)assembly than on the (dis)assembly itself. Further, PBV analyses objects by shape or color and not by functionality. Thus, it may not support repairing processes greatly.

Cobots can support the (dis)assembly and repair of heavy components or products and can execute unsafe and monotonous tasks. Since a complete automation is not feasible in the near future, cobots seem promising, especially because manual processes are among the main cost drivers in high wage countries like Germany.

Nevertheless, a useful implementation of all technologies and solutions is highly dependent on the particularities of the EoU/EoL products within the waste stream.

4. Case study and results

The manufacturing of EVs creates higher environmental impact than the production of conventional cars, and battery production is the major contributor (EEA 2018). Adequate EoL/EoU treatment of batteries may mitigate the impacts by providing alternative material sources and by substituting impactful primary material production. Battery recycling uses mechanical, pyrometallurgical and hydrometallurgical processes, usually in combination (Kwade and Diekmann, 2018). The present case study focuses on the process chain, which stems from the 'LithoRec' research projects. The chain combines mainly mechanical processes with a subsequent hydrometallurgical recovery of the electrode materials (Kwade and Diekmann, 2018) to close material loops by providing battery grade materials. In the following general I4.0 technologies and solutions from Table 3 are evaluated in the context of the recycling operations of Table 2, which also represent the LithoRec processes chain.

Collection: The collection of used Li-Ion batteries may be implemented at OEM car dealers, repair centers or at traditional car recyclers. Data gathering, treatment and storage as well as mining could be implemented jointly, to get valuable information for e.g. route optimization or capacity planning for the logistics and recycling. The smart bin solution is not applicable to traction batteries due to their size, mass and classification as hazardous waste, which leads to logistics and storage restrictions.

*Identification / Classification***:** Product-based information carriers can supply relevant information regarding battery type, age or state of health from the production and use phase. Sensors can subsequently identify the products at the beginning of the recycling process chain. This information can be forwarded through the chain with the help of connecting interfaces as described in chapter 2.1. Visualization has no positive impact due to mainly automated identification processes. ATS could transport the battery systems to disassembly work stations.

Disassembly: As current industry standard, disassembly is assumed to be done manually. Thus, visualization technologies such as AR or a solution like PBV may support workers with additional information and speed up this process. For example, important manual sorting steps, such as sorting according to cell chemistry could be assisted. Data gathering, treatment and mining offers little benefit due to the manual nature of this process. Again, ATSs could be used for transporting heavy battery system parts like the casing to destined collection and storage locations. Battery system casings are usually made of Aluminum and represent a large share of the overall system's mass (Kampker et al., 2016).

Cobots can support workers with the disassembly processes, e.g. by handling heavy and bulky objects like the casings or battery modules. Another application for cobots within disassembly

Table 4
Specific mapping of smart technologies and solutions to Li-Ion battery recycling operations.

	Collection	Identification / Classification	Disassembly	Material separation: **Crushing**	Sorting: **Sieving** & **Classification**
Data gathering (II)	+++	+++	0	++	++
Data treatment & storage (II)	+++	+++	0	++	++
Data mining (III)	+++	+++	0	++	++
Modeling & simulation (III)	++	+++	+	++	++
Visualization (IV)	0	0	+++	+	+
Control (IV)	0	++	+	+++	+++
Smart bin	0	0	0	0	0
ATS	0	++	++	0	0
PBV	0	0	+++	0	0
Cobots	0	0	+++	0	0

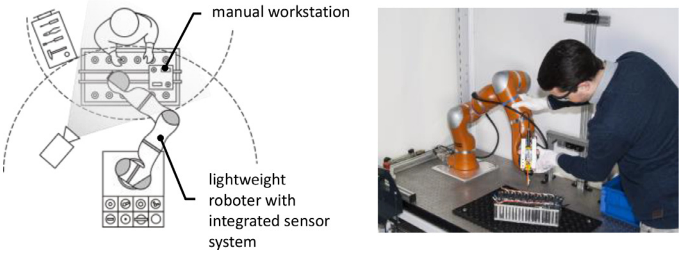

Fig. 3. Cobot disassembly workstation for Li-Ion batteries (adapt. from Kwade and Diekmann, 2018).

can be the automation of monotonous processes like unscrewing, as shown in Fig. 3.

To approximate the economic benefits of integrating cobots into the Li-Ion disassembly, the following estimation is used: For the scenario of a yearly recycling capacity of 3500 tons of spent batteries and manual disassembly operations (two workers), the yearly labour cost can be assumed as 140,000 €. Cobot integration may reduce the necessary workforce to one. Including cobot energy costs (15 kW installed load), the estimated total cost of the new cobot-assisted disassembly system is 76,300 €, resulting in a yearly cost reduction of 63,700 €. With an estimated initial investment of 200,000 €, this results in a payback time of approximately three years.

The environmental benefits of a cobot integration can be assessed with the methodology of Thiede (2018), which considers besides potential improvements also additional efforts for the cobot infrastructure.

Material Separation (Crushing) & Sorting (Sieving and Air Classification): Battery crushing and sorting processes are fully automated processes that show high potential for CPS (I-IV) integration: Continuous monitoring and process parameter control may improve energy and material efficiency of crushing and air classification by analyzing product streams and adjusting process parameters accordingly.

The considered I4.0 solutions have no effect regarding Li-Ion recycling operations as soon as the battery systems are shredded (see Table 4).

Overall, I4.0 technologies and solutions show great potential for this particular CE application, improving process efficiencies, decreasing costs (Kampker et al., 2016) and lowering process energy demands. By improving the overall economic outlook of battery recycling, I4.0 may make this CE endeavor more likely to be implemented on large scale, as remanufacturing and recycling are often only realized, if the business case is economically sound.

5. Summary and outlook

Industry 4.0 solutions may increase the environmental efficiency of recycling and remanufacturing processes due to the supply of necessary product information and decision support, enabling appropriate EoU/EoL treatment. Moreover, the productivity of the EoU/EoL sector and the quality of remanufactured products may rise due to better error detection, repair and reassembly.

A combination of the Industry 4.0 and Circular Economy paradigm indicates positive effects on sustainability. Especially remanufacturing is an interesting field due to expected lower costs and higher output quality, which in turn can improve the market share of remanufactured products with a lower environmental footprint. To support companies combining I4.0 with CE in the sense of recycling and remanufacturing, this paper helps identifying promising technologies and solutions.

Li-Ion batteries are comparatively new products resulting in a large variety of cell chemistries, formats and sizes. In combination with a globally increasing EV market, flexible and changeable battery production as well as EoL management facilities are necessary. As Li-Ion batteries are complex products, for which remanufacturing and recycling companies need detailed product information and understanding in order to achieve the best possible benefit from EoL management. The integration of I4.0 technologies and solutions may help to overcome the challenges of flexibility within and information exchange for recycling.

In the future, the estimated environmental trade-offs from I4.0 integration to remanufacturing and recycling operations and its overall impact may be validated to refine the presented framework.

CRediT authorship contribution statement

Steffen Blömeke: Methodology, Writing - original draft, Investigation. **Julian Rickert:** Conceptualization, Methodology, Writing - review & editing. **Mark Mennenga:** Conceptualization, Methodology, Writing - review & editing, Validation, Supervision. **Sebastian Thiede:** Conceptualization, Writing - review & editing, Validation, Supervision. **Thomas S. Spengler:** Supervision, Funding acquisition. **Christoph Herrmann:** Writing - review & editing, Supervision, Resources, Funding acquisition.

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