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Procedia CIRP 98 (2021) 318–323

www.elsevier.com/locate/procedia

28th CIRP Conference on Life Cycle Engineering

A Life Cycle Oriented Data-Driven Architecture for an Advanced Circular Economy

Lars Kintscher[a], Sebastian Lawrenz[b], Hendrik Poschmann[c*]

[a]Institute of Distributed Systems, Ostfalia University of Applied Sciences, Salzdahlumer Straße 46/48, 38302 Wolfenbüttel, Germany
[b]Institue for Software and Systems Engineering, Clausthal University of Technology, Arnold-Sommerfeld-Straße 1, 38678 Clausthal-Zellerfeld, Germany
[c]Institute of Production Technology, Ostfalia University of Applied Sciences, Salzdahlumer Straße 46/48, 38302 Wolfenbüttel, Germany

* Corresponding author. Tel.: +49-5331-939-45880; fax: +49-5331-939-45882. *E-mail address:* he.poschmann@ostfalia.de

Abstract

Product recycling will become more important in the future to meet the needs of a growing industry. The challenge is to combine this heterogeneous information flows and establish a way for a holistic life cycle management in the circular economy. Therefore, this contribution proposes an automated and data-driven architecture of connecting all the stakeholders to exchange (life cycle) data in order to foster transition towards a circular economy. A general framework is implemented and evaluated on the example of an electric vehicle battery.

Keywords: Industry 4.0; intelligent systems; recycling; information marketplace; sustainability engineering.

1. Introduction

How can the efficiency of recycling processes be increased?

In contrast to highly automated production processes which are demonstrated in the framework of Industry 4.0 and smart factory, the current recycling sector is mainly dominated by manual processes, because it is more complicated to automate a disassembly process instead of an assembly process. However, a transformation of disassembly processes and the recycling domain in general is needed, especially for a sustainable supply of raw and secondary materials.

In previous works, the *lack of information* was already identified as one of the main barriers towards an advanced circular economy [1], [2]. The prospect of an advanced circular economy is characterized by a high degree of automation and digitalization.

Therefore, the goal of this paper is to present a technical framework towards an advanced circular economy to increase the efficiency of recycling processes.

The paper is structured as follows: Section 2 presents the relevant background about information life cycle management and the role of information exchange in the context of the circular economy as well as a comparison of the status quo and our vision. Section 3 depicts the developed overall framework towards an advanced circular economy which is highly inspired by the findings from section 2. The *Recycling 4.0 Framework* shows a way to increase the efficiency of recycling processes, and therefore presents the answer to the initial question. Section 4 describes a current implementation as one instance of the overall model, followed by a proof-of-concept in section 5. A short conclusion and outlook end this paper.

2. Background

As already mentioned in the introduction, the lack of information is one of the main barriers towards an advanced circular economy. The reason for this is that the information must be recorded and passed on over the entire life cycle of

10.1016/j.procir.2021.01.110

products in the circular economy. Without an information flow working reliably, correct decisions are not possible.

2.1. Information Life Cycle Management

In the classical view, (product) life cycle management describes a process to collect and integrate all related information into a homogenous knowledge base [3]. The goal is to improve the processes and collect all relevant information. In the recycling sector, the problem is that the information is only collected by individual companies and for the life cycle of products in which the company is involved. But recycling relevant information or information outside the scope of the producer is not targeted. *An integrated, cross-stakeholder concept is still missing, but necessary!*

2.2. Information Exchange and Impediments

Therefore, information exchange between different stakeholders, such as manufacturers, suppliers, and recycling companies is required. Information exchange herein describes a simple communication of information between two (or more) stakeholders. Technical impediments are, for example, different data structures (unstructured, semi-structured or structured), various formats (SQL vs NoSQL, CSV, XML, JSON), and schema related problems (lack of integrity, inconsistency, and so on) [4]. Another major challenge here is the different naming and understanding due to missing standards [5]. Nevertheless, besides the technical issues, which can be bridged for example by common ontologies, adapters, or standards, the will to share information is still missing. Stakeholders want to protect their company secrets (e.g. material content of a lithium-ion battery [2]) on the one hand, and on the other hand, (monetary) incentives are missing. For this reason, a data and information marketplace as an efficient political and legal framework for sharing data and information relevant to the circular economy was already proposed in previous work [1], [2], [6]. Irrespective of the fact that this creates incentives and an ecosystem for the data and information exchange, new problems still arise. Data and information are not like physical products and therefore difficult to trade. While they are expected to meet various data quality criteria, the integrity of the data and information source is important and a clear marketplace framework is still missing and not standardized in comparison to other e-commerce platforms [7], [8].

2.3. Industry 4.0, Digital Twin and Recycling

The continuing developments in industry have led from specific automation concepts to advanced, self-optimizing, cyber-physical systems in the concept of Industry 4.0 (see Fig. 1). Important paradigms, such as seeing a factory as a network of communicating functionalities making individual decisions based on given performance indicators lead to higher efficiency and improved quality. Self-optimization and cognitive abilities

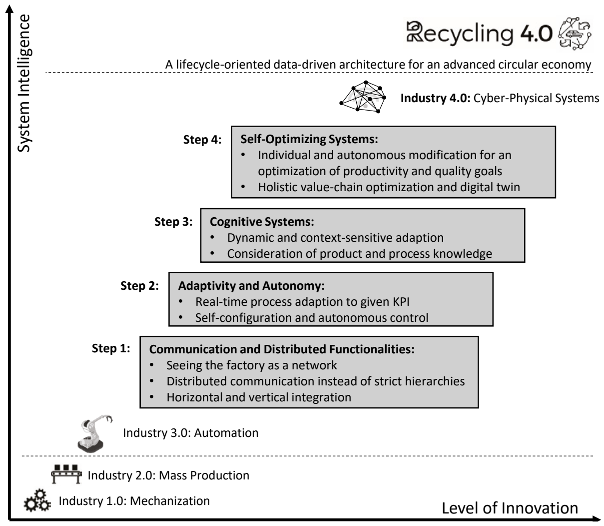

Figure 1: Development of system intelligence in industry

are already present in research and become more and more visible in real industrial applications. In order to successfully implement such systems, a holistic information management concept is required. The idea of a fully-digitized product equivalent is referred to as a “digital twin” (DT). DTs can both supply cyber-physical systems with real world information in terms of life cycle management as well as provide simulation possibilities and analysis options to plan or predict real world behaviour in a digital environment [9].

2.4. Recycling and Remanufacturing

In the concept of a circular economy, the different options for end-of-life (EoL) processing are of great importance for the overall feasibility of the entire process. Recycling as a way of recovering the materials and remanufacturing as a process to re-establish the initial functionalities of certain parts and subassemblies are the economically most important EoL-options in terms of economic output and companies involved. Most business models in the circular economy are therefore based on these two options, primarily on recycling [10]. However, in an evaluation based on sustainability goals, recycling is the least favorable option and reduction and reuse should be preferred (3R principle). The integration of Industry 4.0 techniques in this field is not yet fully advanced, even though the potential has been widely acknowledged [11], [12]. Especially the automation of expensive (manual) process steps, such as disassembly, is desirable and requires the implementation of cognitive system abilities relying on Industry 4.0 technologies [1].

2.5. Problem Statement

By viewing all the Industry 4.0 approaches and the manufacturing processes nowadays, the recycling sector is still faced with the mainly manual processes. Before introducing the Recycling 4.0 framework, the main reasons for the largely manual processes are summarized:

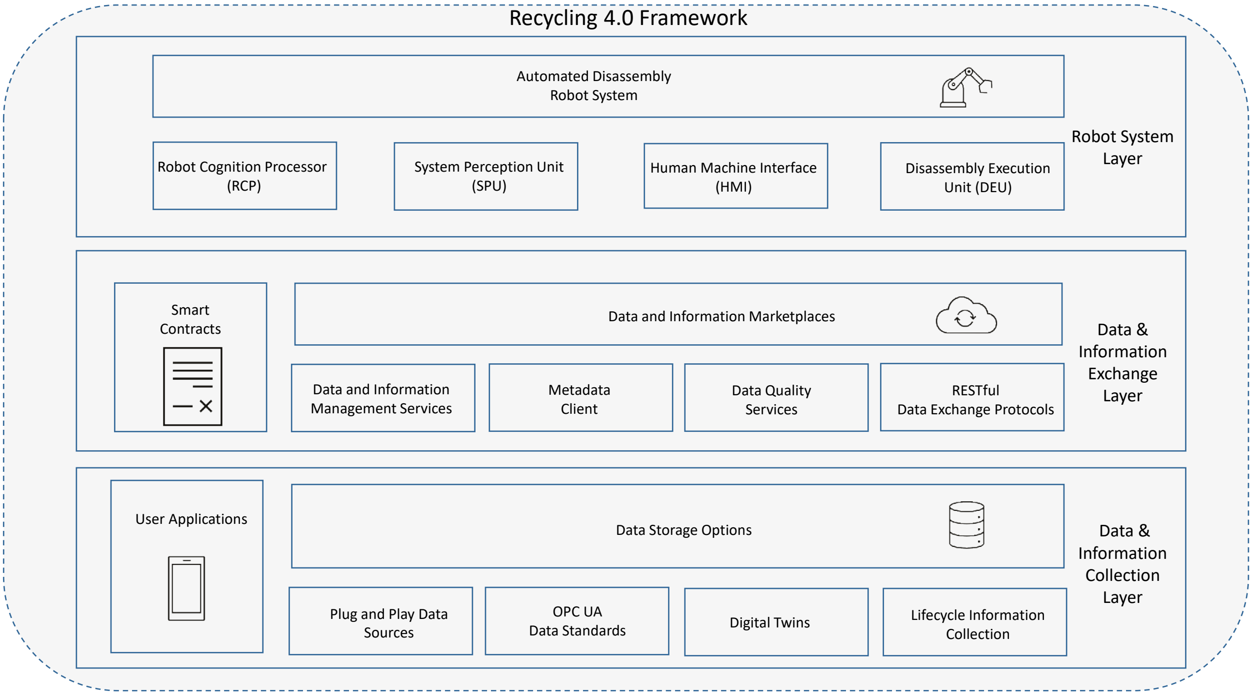

Figure 2: Framework overview

- No standardized processes compared to production: One of the main goals of Industry 4.0 is to overcome the chaos of multiple standards and to enable interoperability.
- No established holistic and closed-loop supply chains over the whole product life cycle:
  There are well-established supply chains for the production, as well as (partly) for the recycling, but there is a break between both chains. Closed-loop supply chains are still missing.
- Return of the EoL-products only after many years: Most products are used for a varying number of years. It is difficult to predict exactly when the products will be returned, which leads directly to the next challenge for the recycling sector:
- High variance in the return of products:
  Complementing the production industry, the recycling sector has to deal with a huge variance of different products and their conditions.
- Lack of information exchange between different stakeholders:
  There is no clear information exchange between the different stakeholders. Furthermore, some information, especially dynamic life cycle information is not even collected.

3. Recycling 4.0 Framework

The overall Recycling 4.0 framework is shown in figure 2 and designed to tackle these challenges.It is divided into three main layers, which will be introduced in the following subsections.

3.1. Data and Information Collection Layer

As already mentioned, the lack of information is one of the main challenges towards an advanced circular economy. Besides the problems from section 2.2, some necessary information is currently not even traced and collected. User applications can help to collect life cycle data of products and trace their conditions. Plug and play data sources enable simple possibilities for the stakeholder to bring their data into the overall system and share them (for example via the data and information marketplace). By using the Open Platform Communications Unified Architecture (OPC UA) standard, which is already well established in the industry [13], a couple of technical issues can be overcome, such as different standards and data formats. Furthermore, a concept for DTs based on OPC UA as well which integrates recycling relevant information into digitized products was developed. Moreover, the framework offers different data storage options, such as cloud options (e.g. *Google Drive*, *Microsoft OneDrive*), centralized local storage options as well as decentralized storage options, like *IPFS* and *BigChainDB*. By offering all these different options and possibilities, every stakeholder retains control over the data, ownership, and other issues, such as the IT security policy.

3.2. Data and Information Exchange Layer

The *Data and Information Exchange Layer* enables the data exchange between different stakeholders by providing a legal framework. The main element here is a data and information marketplace, which is a platform where different stakeholders

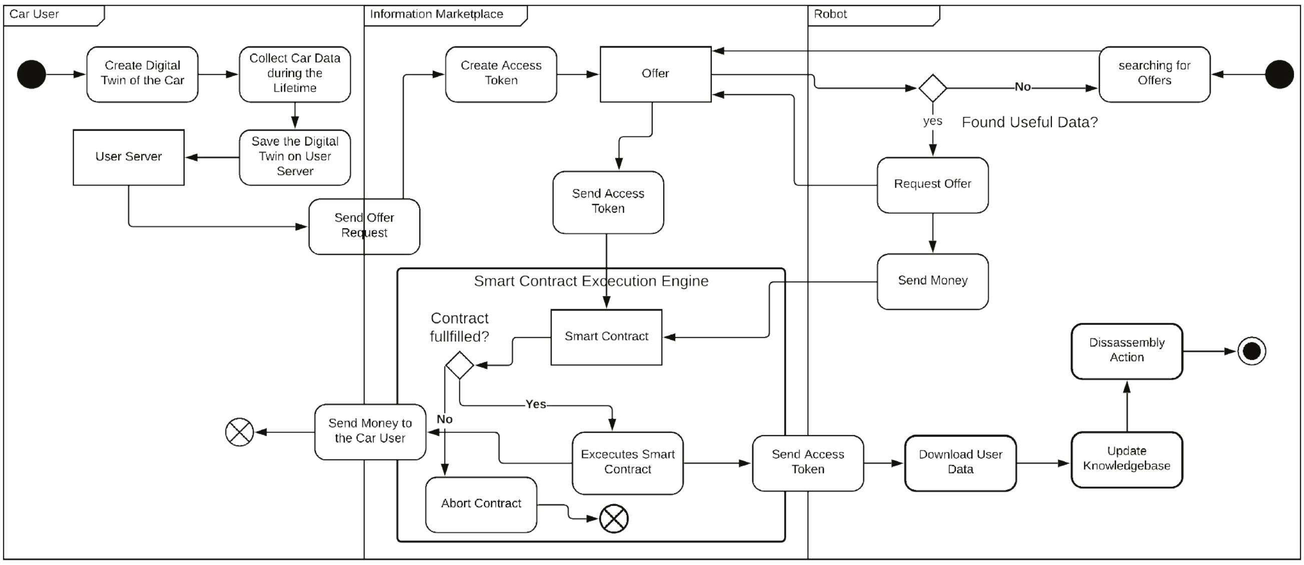

Figure 3: Scenario

along the circular economy can connect to trade and exchange data and information.

RESTful data exchange protocols (*REpresentational State Transfer*) and interfaces to the marketplace bridge this layer to the collection layer and provide an easily accessible and standardized way to connect to the platform and participate. Different services, such as the data quality services and the data and information management services support the stakeholders in trading their data and information as well as in a consistent life cycle information management. Furthermore, the metadata client enables an easy way to analyze the datasets and label them with metadata. Smart contracts provide an efficient digital way for actions and agreements between the different stakeholders to the terms of a contract. In consequence, they enable an option for autonomous devices, such as robots, to sign contracts autonomously, for example, to buy or sell data.

To overcome political hurdles, such as different data protection laws, the overall marketplace offers different data storage and exchange options. The data providers do not need to store any instances from the datasets in the marketplace, and the data exchange will take place via a secure runtime. A more detailed look at these approaches and architecture is shown in [14].

3.3. Robot System Layer

The *Robot System Layer* is the base for automated disassembly machines, which will be able to handle a high variance of products. The system perception unit represents the machine’s visual sense and can recognize different products by training a neural network for classification. The robot cognition processor handles disassembly requests, based on the system perception unit, and data or information from the marketplace and makes decisions about the relevant EoL-option. A human-machine interface (HMI) manages interaction which provides the system with new input or correction. Finally, the disassembly execution unit dismantles the different products.

4. Implementation

The proposed framework was tested in a prototypical implementation. Section 4.1 shows the overall architecture of the implemented prototype. Section 4.2 describes the the *Data & Information Collection Layer* with creation of a DT of a car with an electric vehicle battery (EVB). In 4.3, the *Data and Information Marketplace* as central part of the *Data & Information Exchange Layer* is explained in detail and section 4.4 describes the *Robot System Layer* with the *Automated Disassembly Robot System* (ADRS).

4.1. Scenario and overall architecture

Fig. 3 shows the scenario as the base for the prototypical implementation. A DT of the car is created and updated with lifetime data in the use time of the car. The DT and its data is stored on a *User Server*. The user can decide to share life cycle data. In this case, an offer including an access token is created and sent to the *Data and Information Marketplace*. The ADRS can search for offers on the marketplace for the vehicle which should be disassembled. The *Smart Contract Execution Engine* handles the buying process and the money transfer, resulting in sending the access token to the ADRS enabling it to access the *User Server*.

Fig. 4 shows the overall architecture of the prototype for implementing the scenario including the components from the Recycling 4.0 framework as well as their interfaces. The implementation of the different components will be explained more detailed in the following subsections.

4.2. Implementation of the Data & Information Collection Layer

The first step within the *Data & Information Collection Layer* is the definition of an information model for the DT. Here, the information model of the EVB by use of OPC UA is defined. This is done by the manufacturer of the battery as the

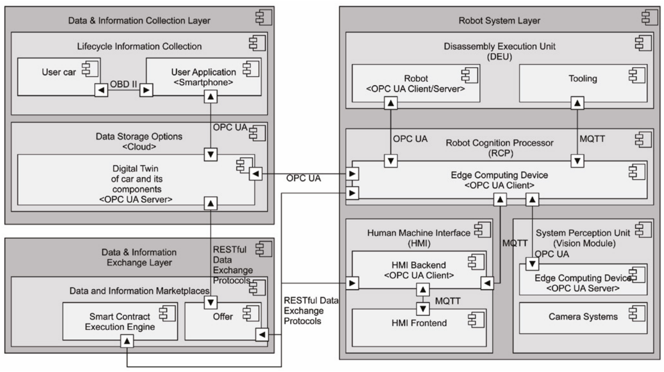

Figure 4: Overall architecture

manufacturer knows about used materials, connectors, etc. in the battery. The DT of the car is now expanded by information about the EVB. This process can also be done with other suppliers, so as a result, the DT of the car is an implementation of the collection of information models of the car's components. A car as a physical object has a DT now. But the DT in the Recycling 4.0 framework should not only consist of manufacturing data. Furthermore, it should be expanded by life cycle data, which can be analyzed in the disassembly process later. So the next step is to fill the DT with data from the use phase of the car, e.g. with information about the state of health (SoH) of the battery. In the prototypical implementation, this was done by a user application installed on a smartphone connected to an on-board diagnostic adapter (OBD-II). The user application is an OPC UA client connecting to the OPC UA server implementing the DT of the car. OPC UA also offers to historize data, so it is possible to save the change of values with their historical timestamps. The OPC UA server implementing the DT of the car is referred as *User Server* in the scenario, though it can be a server in the vehicle manufacturer's infrastructure, who offers the storage of lifetime data as a service for the customer. The server can be embedded in a cloud infrastructure to provide enough data capacity. But an important aspect is that the user and not the vehicle manufacturer can decide about sharing the life cycle data. If the life cycle data is shared, access to the DT is offered via the *Data and Information Marketplace*.

4.3. Implementation of the Data and Information Exchange Layer

The *Data and Information Marketplace* builds the bridge between the different stakeholders. In the implemented example, the *User Server* sells access to the DT of the car. An access token is generated and stored in the marketplace. The *User Server* as well as the *Robot Cognition Processor* of the ADRS have RESTful data exchange protocols implemented: The *User Server* for creating an offer on the marketplace and the *Robot Cognition Processor* for searching through offers and to buy access to the DT of the car. The trading process is handled by the *Smart Contract Execution Engine*, so the money transfer and the access token are executed in a smart contract, which ensures a fair trade scheme.

4.4. Implementation of the Robot System Layer

The ADRS is implemented as an agent-based system, using a collaborative robot and task-specific edge computing devices [15]. The ability to exchange product and process specific knowledge for each individual part directly between the superordinate marketplace and the field level of the robotic control system marks a novel approach in EoL-treatments. The system consists of a *Robot Cognition Processor* for AI-enforced decision making and overall coordination [16], a perception unit for identification, localization, and part rating, and an execution unit with a connected tool system, also capable of diagnosing e.g. screwing processes. An intuitive HMI with a web-based user application and a voice control interface (see e.g. [17]) completes the disassembly system for easy-to-use operation. As shown in Fig. 4, besides Message Queuing Telemetry Transport (MQTT), some of the components in the ADRS use OPC UA for internal communication. But OPC UA is also used for external communication: after accepting an offer from the *Data and Information Marketplace*, the received access token is used for establishing an OPC UA communication with the *User Server* and as a result, the *Robot Cognition Processor* can read and analyze the DT of the car. After successful operation, writing process data to the DT is also possible.

5. Function Evaluation / Proof of Concept

One source of information for the DT of the EVB is the car itself and the user's smartphone, which reads the car data. It was possible to read the SoH of a VW E-Golf, so the DT of an electric vehicle and its EVB could be updated during the use phase.

A central aspect of the proposed information management framework is the vertical interoperability between shop floor systems and the superordinate database. As a part of the function evaluation, it is shown that the system is able to autonomously gather product data from the machine vision module of the robotic system and appends this information to the DT model in the OPC UA server structure. In order to provide relevant information in terms of life cycle options, a visual status of the part is also documented by detecting optical damage, such as rust or major scratches. This augmented data model is then used to decide upon the final utilization option and therefore determines the overall level of disassembly as well as suitable EoL options.

In terms of the planning approach, the framework presented can in this way reach the third stage of the development to a fully integrated Industry 4.0 (compare Fig. 1), if not be a self-optimizing system in connection with a holistic DT model supplied by the manufacturers. However, regarding the actual execution of fully automated disassembly, further development in the area of tooling and tool changing as well as destructive and semi-destructive is needed. The function evaluation was carried out positively for non-destructive disassembly by removing screws as fasteners. A quantitative evaluation in regard to the economic feasibility needs to be performed in further research.

6. Conclusion and Outlook

A technical framework to increase the efficiency of circular economy processes in the form of the *Recycling 4.0 Framework* was presented. Complementing manufacturing processes, the recycling domain is dominated by a high variance of products and conditions, almost no fully established closed-loop supply chains and a lack of information, as well as a missing data interoperability standard. The framework is tackling these challenges on different layers. The data and information collection layer supports the tracing and collection of different data and information such as life cycle data and bridges the interoperability by using OPC UA as a standard. Furthermore, it extends the well-known concept of digital twins to include recycling relevant information. The information exchange layer provides a data marketplace, a legal frame for networking between stakeholders, and the exchange of information. By using the data and information model, the robot system layer enables an automatized disassembly processes instead of the current manual disassembly.

The framework is demonstrated by the implementation of these different layers in a working prototype. Within a life cycle user application for electric vehicles, it is possible to trace information about the EVB. This information is sold via a data and information marketplace to an autonomous robot. The robot uses this information to rate the current state of the EVB and combines it with the visual information. Finally, it can propose a decision for the level of disassembly.

All in all, it is demonstrated that the framework is working under real conditions with actual products and automation hardware and that it is an important step towards an advanced circular economy. Collecting and sharing recycling relevant information is one of the key components for a high standard of automation, and the *Recycling 4.0 Framework* can support it. But in the end it depends on the industry to adopt it.

In the next steps of our research, results with additional findings in the overall project *Recycling 4.0* will be combined and integrated. There, different views and layers for finding the right balance, between economic and ecological interests are investigated. One main focus there is also to find out a model for a fair pricing model for data and information.

Furthermore, it is planned to transfer the framework to all phases of the product life cycle and no longer focus solely on EoL. A transfer to other product domains such as WEEE is also in progress.

Acknowledgements

This paper evolved from the research project *Recycling 4.0* which is funded by the European Regional Development Fund (EFRE | ZW 6-85017703, ZW 6-85017297) and managed by the Project Management Agency NBank, Germany.

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