Recycling 4.0

An Integrated Approach Towards an Advanced Circular Economy

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ABSTRACT

Resource scarcity is a global challenge, especially in E-mobility. Currently, Electric vehicles (EVs) are considered as an attractive option on a pathway towards low emission mobility. Nevertheless, due to the increasing sales and acceptance of EVs, new challenges arise regarding the scarcity of utilized materials, especially regarding lithium-ion battery systems. Battery production is responsible for the major share of the environmental and economical impacts of the overall EV production. In order to tackle these challenges, resource-efficient processes and a circular use are necessary. Today, a variety of new Industry 4.0 technologies (such as high integrated production systems) are affordable and have reached maturity. Like Industry 4.0, also Recycling 4.0 aims at digitalization of processes but with the focus on the End of Life stage of products. The main goal of the German research project Recycling 4.0 is to develop approaches, which enable advanced information creation, transfer and use along the entire supply chain. In this work, a holistic approach towards an advanced circular economy (Recycling 4.0) is shown. This approach combines methods from different areas (such as economics, mechanical engineering, and computer science) and paves the way towards an advanced circular economy. This paper introduces this approach by discussing the current situation of EV recycling and related judicial fundamentals. Furthermore, the overall approach is introduced, and the discipline-specific sub-approaches are discussed in detail.

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CCS CONCEPTS

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1 MOTIVATION & INTRODUCTION

Climate change is identified as one of the most anthropogenic challenges of the 21st century. Because of its significance, the United Nations Agenda 2030 includes sustainable consumption and production patterns as one of the 17 sustainable development goals [1]. There are several approaches to reducing the emission of greenhouse gases (GHG) in order to prevent the progression of climate change and to save the world of its negative effects. One mitigation option are EVs substituting vehicles with internal combustion engines. In 2018 5.1 million new EVs sold, up to 2 million more in contrast to the previous year [2], constituting an upswing in global demand. However, the rising demand leads to new challenges that need to be addressed. Resources, which are necessary for the production of the electric vehicle battery, are not always mined under fair conditions for the workers and are also associated with environmental impacts. Recycling of the End of Life (EOL) batteries can help at this point to reduce the amount of resources needed to be mined by the supply of secondary materials.

Due to the relatively new and therefore steadily improved technology of traction batteries, the heterogeneous market consists of various battery cell designs and chemistries. This high product variance is challenging for the recycling sector, which keeps its efficiency low and costs high. High product variety results in manual disassembly which leads to significant costs in high-wage countries [3]. The productivity of downstream mechanical and metallurgical treatments is not that high yet and could be improved by a strict separation of different battery chemistries. The main barrier for efficient recycling is the lack of product information starting with contained materials, used joining techniques and history of product usage [4], [5].

For decades, manufacturing showed potential regarding the implementation of digitalization in industry towards Industry 4.0 (I4.0). I4.0 combines well-established automation technologies with approaches from computer science, such as complete networking and artificial intelligence. The use of digital methods and tools within the recycling sector is still uncommon but can become a promising solution for improving recycling efficiency and transparency by using product and market information over the product life cycle [6].

Therefore, this paper presents an integrated approach to handle the upcoming return of EOL EVs, which number will rise in a few years. A second wave of electric and electronic waste similar to a waste of electric and electronic equipment (WEEE) without an efficient recycling system should be avoided. This ensures that a second wave of electric waste as it had occurred in the past will be avoided. The Recycling 4.0 approach is exemplarily demonstrated for the case of traction batteries and information and communications technologies (ICT) at their End of Use (EOU) of an electric vehicle. This does not mean that these components already have achieved their EOL status. Through a smart combination of approaches from the field of digitalization and by linking the forward and reverse supply chain an advanced circular economy (ACE) can be achieved [7].

The second chapter gives necessary background information about the actual situation of traction battery recycling. It describes the judicial fundamentals, the forward and reverse supply chain as well as the disassembly process and resulting technical problems. The overall approach presents how problems in the recycling of traction batteries can be tackled. The ACE gets introduced and the specific subparts explain how to implement the ACE. Finally, a conclusion is drawn and future research directions are derived.

2 BACKGROUND

2.1. JUDICIAL FUNDAMENTALS

In the European Union three major instruments influence or regulate the recycling of lithium-ion batteries (LIB) (the most frequently used traction battery) from EVs The EU Action Plan to close the loop (COM/2015/0614 final [8]), Directive 2000/53/EC on EOL vehicles [9] and Directive 2006/66/EC [10] on (waste) batteries and accumulators. The action plan for the closure of the circular economy provides 54 measures (completed or in the process of implementation to date) which favor the closure of product life cycles [11]. The EU identifies five priority sectors whose value chains are to be accelerated towards a CE. These include the "critical raw materials" sector, where the LIB raw materials cobalt and graphite are part of the EU's list of critical raw materials. They are therefore subject of high supply risk and are of great economic relevance [8],[12]. The two Directives 2000/53/EC and 2006/66/EC are of fundamental importance for the implementation of the closed-loop recycling management for LIB from EVs. According to Directive 2000/53/EC, 95 % by weight of an EOL vehicle must be reusable and/or recoverable and 85 % by weight must be reusable and/or recyclable. In addition, Article 6 requires that all hazardous materials and components, including the traction battery, must be removed before further treatment [9]. After extraction, Directive 2006/66/EC classifies traction batteries as industrial batteries. For the recycling of LIBs, a minimum efficiency of 50% of the battery weight is required and the principle of extended producer responsibility is applied [10].

2.2. CURRENT FORWARD AND REVERSE SUPPLY CHAIN

The forward and reverse supply chains used to be uncoupled. Hence, cooperation and interdependencies mainly occurred within each of the supply chains. The process of the forward supply chains starts at the raw material supplier. It carries out the mining and processing of raw materials. Depending on the battery material, the material occurrence is spread around the world [13]. Therefore, materials need to be shipped to the battery production, which is mainly located in Asia [14]. Within the battery production, different structures were implemented. In some supply chains, the manufacturing is highly integrated within one company, which carries out all processes from the coating production to pack assembly. However, other supply chains are highly disintegrated and specialized companies for each production step cooperate in order to produce a battery pack [15]. After the battery pack production, the original equipment manufacturer (OEM) usually assembles the battery system and sells it within a product or as spare part to the customer.

After use, the customer hands over the battery towards the reverse supply chain. Herein, the battery can either be disassembled at a workshop in case of exchange or at a disassembly facility in case of the take-back of an entire car. Afterwards, the battery is transferred to the recycler. The recycler carries out the recycling processes and then sells the regained materials to the forward supply chain [16]. Furthermore, different options like 2nd-life and remanufacturing are developed and established in pilot scale. Therefore, the reverse supply chain is divergent (see figure 1).

Due to supply chain management the information exchange within the forward supply chain is comprehensive and only few information deficits occur. However, the information flow is interrupted at the customer. Furthermore, customers usually share few information with the reverse supply chain. Therefore, a variety of information deficits occur in the reverse supply chain, such as product design, return quantities, and state-of-health [15].

2.3. DISASSEMBLY PROCESS AND TECHNICAL PROBLEMS

The recycling sector is currently characterized by disconnected links regarding information flow and EOL value chains. Most process-steps within dismantling companies are carried out manually, therefore being relatively expensive in terms of running costs and volatile in quality as well as output. In respect to the four steps of the recycling chain [17], from collection and sorting via preparation and disassembly to mechanical and chemical processing and finally to the recovery of raw materials, disassembly processes usually requires manual labor due to complex products. The efforts depend on the product complexity itself and design issues, making disassembly more complex than general assembly tasks, be it for recycling or 2nd-life and remanufacturing purposes [18]. Many problems associated with the recycling of various products result from an inefficient disassembly process. A range of inhibitors regarding the disassembly process has to be overcome for the successful economic feasibility of concepts on an industrial scale, e. g. the flexibility of automation solutions, handling of material diversity, cost of logistics, workforce qualification and low average utilization. Efficient automation and mostly autonomous machine operation could strongly reduce the amount of planning requirements and therefore increase the cost-efficiency of the overall process. Pursuing robotic disassembly processes concerning current technological developments such as machine learning and advanced information exchange methods provide promising solutions to these major challenges [19],[20].

2.4. INFORMATION PLATFORMS AND LIMITATIONS

The complex material structures and compositions of the vehicles and the LIB require an adequate information base for an efficient EOL process chain and to achieve the recycling goals [21]. Therefore, digital solutions are required. The International Material Data System (IMDS) is a globally standardized exchange and management system for material data in the automotive industry and contains information about material and chemical compositions of components, semi-finished products, and materials related to the automotive industry [22]. Besides, the electronic waste record is required in Germany, which certifies the proper disposal of hazardous substances [23]. But the existing solutions now are not sufficient and they do not include all the information.

In other sectors in recent years, there have been many ideas proposing data or information marketplaces, intending to give back the data ownership to the data producers and let them decide whether they want to share their personal data or not. The IOTA Marketplace [24] is a decentralized data market place that aims to make IoT data available to any compensating party. The Mobility Data Marketplace enables different parties to offer mobility data [25]. Streamer is a data marketplace that provides real-time data steaming and Datum marketplace focuses on empowering the users to take back control of the data [24]. Although these projects focus on buying, selling and real time streaming of data and most of them are running prototypes for small data streams, such as IoT sensors. But all of them do not include recycling relevant data at the moment and they are not made for companies or consortiums as data providers.

3 OVERALL APPROACH

3.1. MATERIAL FLOW, COMPONENT AND INFORMATION FLOW SYSTEM

One of the main problems, which hinders the efficiency in the area of recycling, is the lack of information between the different stakeholders [26]. In an ideal market, according to the Coase theorem [27], the definition of property rights leads to a Pareto efficient allocation, provided that no transaction costs are present. In a Pareto efficient state or Pareto optimum, no market participant could improve his own position without weakening the others. Transaction costs include, among others, the acquisition and analysis of information needed for decision making. Therefore, as Ronald Coase points out, all market participants must be informed completely, in time and at no charge.

However, real market participants do not have undiminished information to support this assumption. It can be concluded that a lack of information leads to costs and should be avoided [27]. In order to circumvent this pareto-inefficient state that prevails in real markets, at least the following questions must be answered for the respective stakeholders in regard to an exchange of information:

- Which information does a stakeholder need?
- Which information can they offer?
- Why does the exchange of information fail?

Furthermore, the rules of an orderly exchange of information [28] and the respective quality of information must be taken into account [29].

Table 1 shows a rough representation of the information needs, offers and points of conflict of the relevant stakeholders in a circular economy of traction batteries. It can be seen that various information needs of individual stakeholders are covered by the offers of other stakeholders, but that an exchange of information does not take place due to the potential for conflict. Thus, all stakeholders in the chain behind the customer or user are interested in information about the State of Health. However, an exchange of information does not take place due to intellectual property or data protection regulations.

In addition to the information flow system, in which existing or non-existing information could influence the decisions of each stakeholder, flow systems are developed for the materials and components of the traction battery. The three systems will then be linked together, making the advanced circular economy visualizable, controllable and assessable. For this purpose, a system-dynamic approach (SD) will be pursued, which will be developed through the following steps:

- The recording of all investments / physically active units along the circular economy, including trading systems,
- The capture of material flows, especially waste flows and flows from product processing, the collection of input specifications for various component and material flows, the identification of information needs and offers as well as the conflict

potential of the information trade of each stakeholder and its inclusion in the system,
- The creation of a material flow system by means of an SD model, which is subsequently extended by the component and information flows and the validation of the simulation results from the SD model,
- Developments in recent years clearly show that there is a fundamental interest in an exchange of information. Thus, more and more companies along the circular economy are coming together to bundle expertise, save costs or generate synergies.

3.2. CLOSED-LOOP SUPPLY CHAIN MANAGEMENT

Due to increasing resource scarcity, rising material prices and potential supply bottlenecks, companies of the forward supply chain increase their efforts regarding EOU/EOL. This results in interactions between the forward and reverse supply chain and therefore growing interdependencies between the supply chains. However, the production planning of the forward supply chain and the recycling planning of the reverse supply chain are separated. Furthermore, most companies only consider their local optimums neglecting the interdependencies. Such uncoordinated local planning usually leads to non-optimal decisions regarding the whole supply chain [31]. Hence, closed loop supply chain management (CLSCM) is needed in order to achieve the supply chain-wide optimum. Therefore, coordination mechanisms give economic incentives for companies to align the local plans to the supply chain optimum. In order to implement a CLSCM, two main steps are needed.

Firstly, adequate planning models enable each company to create a production or recycling plan according to their local optima. For production planning, a large variety of different models fit the requirements of LIB production. However, models for recycling planning are less advanced. Especially, the different activities in the EOL, such as recycling, refurbishment, remanufacturing, and reuse, as well as recycling efficiency, need to be integrated into the existing models. Therefore, new approaches for the recycling planning of LIB are developed within the research project.

Secondly, adequate coordination mechanisms must be developed which provide the incentives to encourage companies to plan in terms of the supply chain. The complex structure of the supply chain poses a challenge, as the incentives have to be distributed over several participants at several levels. By the interaction of adequate planning models

Table 1: Coarse representation of the information requirements, offers and points of conflict in a circular economy using the example of the traction battery [30]

Stakeholder	Information requirements	Information offers	Points of conflict
Electrode, cell and module manufacturers	• Quality and purity of the raw material • Country of origin (keyword: working conditions in cobalt mines in the D.R. Congo) • Knowledge about the performance of your own product on the marketReturn behavior	• Product and variant type • Quality, construction, material content and performance limits of the components	• Manufacturers mostly located outside the EU • e.g. material contents are part of the company secrets
Battery system manufacturer and OEM	• Quality, construction, material content and performance limits of the components • Origin of raw materials • Usage behavior of the customers • Return behavior	• Product and variant type • Installation plans • Creation of an interface in the BMS for readout	• Company Secrets • Customer-specific vehicle usage data under data protection
Customer/ user	• SOH of LIB ➢ resulting in a residual value of the battery		➢ Data protection!
Initial treatment (workshop, collection point and/or dismantling facility)	• Product and variant type • Value of the LIB • Installation data • Disassembly sequence • Contents of the components • Recycling potential of entire or individual component groups • Potential dangers • Storage and transport of the LIBs • Return behavior	• Condition of the LIB • (possible in the future) decision on Reuse, Repair, Reman or Remat • Depth of disassembly • Conclusions about return flow behavior to battery manufacturers and OEM	• Different construction of the LIBs of different manufacturers • No standardization possible • Additionally, trained personal, storage places and transport • Trade secrets and data protection of upstream stakeholders
2nd-life provider	• Product and variant type • SoH of the LIB • Condition of the LIB • Design • Access data to BMS • Return behavior	• Knowledge about the further "battery behavior" ➢ Long term test in practice • Conclusions about return flow behavior to battery manufacturers and OEM	• BMS access data • Uncertainty about market development for 2nd-life applications
material-oriented recycler	• Product and variant type • Material contents • Design • Future change of product characteristics • Return behavior	• Conclusions about return flow behavior to battery manufacturers and OEM • Quality and quantity of the secondary raw materials produced	• Company Secrets

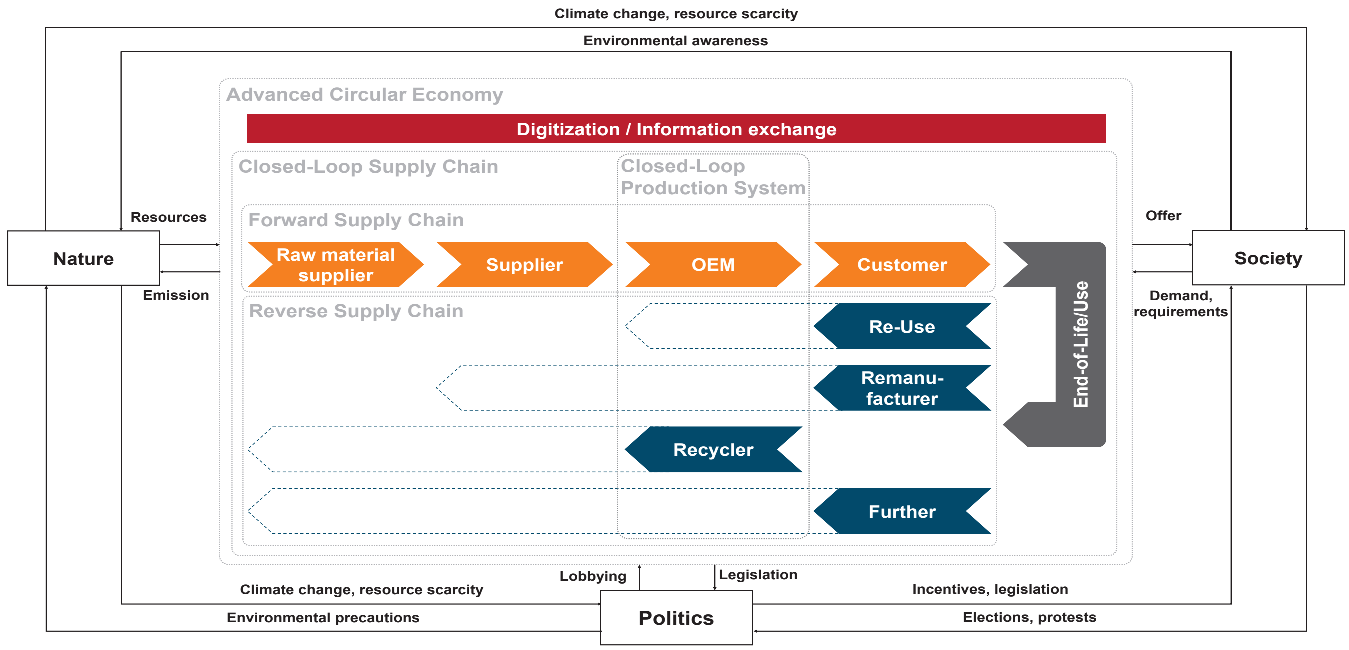

Figure 1: Overall Approach for an advanced circular economy (ACE)

and coordination mechanisms, supply chain wide optima can be achieved. The implementation of such a CLSCM usually leads to increased trust and interdependencies between the companies [32]. Therefore, companies tend to remove the barriers for information sharing in these alliances. Many examples occur in practical applications of forward supply chains, e.g., the distributed development and production of cars. Furthermore first applications can be found in recent alliances of battery recyclers and OEMs, e.g., Audi and Umicore [33]. Therefore, CLSCM can overcome some points of conflict, such as company secrets (see Table 1). The findings provide valuable references for the implementation in practice.

3.3. CLOSED-LOOP PRODUCTION SYSTEM

A stricter legislation as well as an increasing societal awareness in regard to social and ecological standards incentivizes the manufacturing industry to integrate reverse product and material supply chains. Recycled (secondary) materials have a significantly lower environmental impact in comparison to primary materials and should therefore be the prioritized source for manufacturing [34]. A promising approach for integrating reverse supply chains is a closed-loop production system (CLPS) shown in figure 2, which combines production and retro production operations, such as remanufacturing and recycling operations, within a single system to optimize resource and cost management [35].

The goal of a CLPS is the value creation by transferring product and material flows into new goods, with the provision of material and components for new products by remanufacturing and recycling EOU/EOL products.

Due to volatile reverse flows, a CLPS needs to be flexible and adaptable in regard to product, process and volume quantity as well as quality changes. The production and the EOU/EOL of a product can be separated for many years. This requires reverse production technologies that are able to handle a variety of products, components and materials, which may additionally be different from the forward production. Therefore, life cycle oriented product planning and design is required (e.g. design for recycling) and needs to reflect production as well as reverse production planning. Due to the time gap between the production of new and the reverse production of used products, also technology developments must be accounted for, e.g. through technology forecasting. The efficient processing of diverse products within one system requires extensive product and market information from different stakeholders, such as raw material suppliers and customers (see also paragraph III.A).

The system requirements mentioned above result in the inherent production system shown in figure 2, which is organized in a matrix production system which is capable of manufacturing and assembly as well as disassembly and remanufacturing. Reverse production steps are operated in parallel to the forward production processes, so that the remanufactured parts, components and materials can be directly supplied to the manufacturing lines. Low quality EoU/EoL products as well as process waste will either be fed into the in-house recycling or given to external partners for a symbiotic re-use, remanufacturing or material recycling [36].

One promising example can be the LIB system, whose production makes the largest contribution to the environmental and economic impact of EVs [37]. Within a CLPS, reverse components (e.g. battery cells) or materials (e.g. active materials) can supply the manufacturing lines of new LIBs and reduce the impact of EV production.

The required flexibility of a CLPS necessitate product and market information over the product life cycle to obtain overall transparency, which can be provided by different I4.0 technologies and resulting aggregated information within the central information marketplace (see paragraph III.E).

The resulting research question is the evaluation of the overall impact of the implementation of the described integrated production- and retro production system. Therefore, the goal is the implementation of a method to plan, manage and operate complex integrated production- and retro production systems and to evaluate the economic and ecological impacts of CLPS.

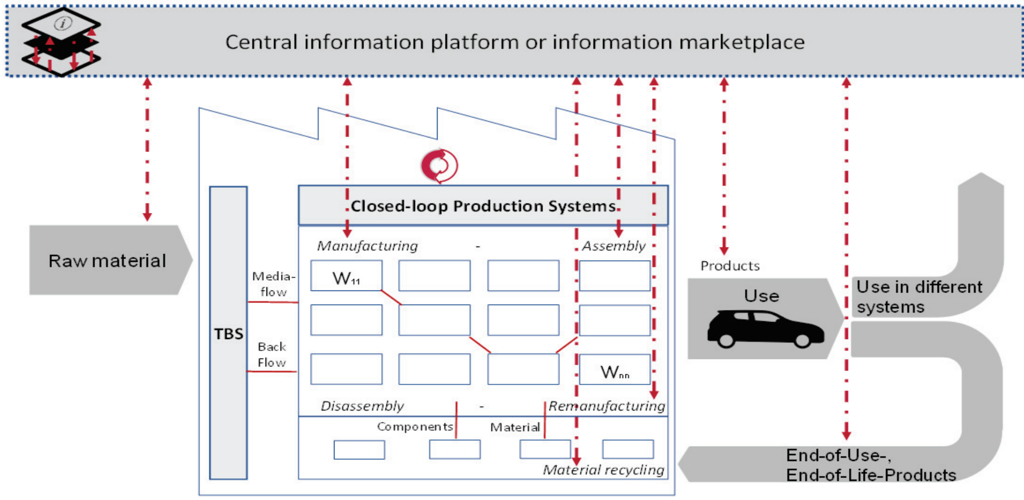

Figure 2: Structure of a Closed-loop Production System [24]

3.4. ROBOTICS

An informationally integrated disassembly system by the use of robot cognition is developed, based on the information input described in Table 1. Following the continuous improvement of sensor technologies and computational capacities in recent years, it is reasonable to employ these tools in combination with robotic systems to reach an advanced state of system able to fulfil the demands of highly complex tasks such as in disassembly. The field of cognitive robotics embodies the study of knowledge representation and reasoning problems in dynamic and incompletely known environments by a robotic agent [38]. Hence, to optimally fulfil disassembly tasks and operations, a robot cognition system is developed. In Recycling 4.0, electric vehicle traction batteries were chosen as object of research. The proposed system considers the described requirements for a human-robot-collaborated (therefore referred to as "hybrid") disassembly up to the level of battery modules (see Table 2).

The integration of the closed-loop supply chain's information flow right up to shop floor level marks the most important aspect of this robotic system setup. Being a key element of the ACE, the actual execution of EOL-treatments as an integrated element actively contributing to information based economic value added is unique. Consecutive to works of Vongbunyong [39] and Jungbluth [40], the architecture of the system represents a structure of communicating agents which have to carry out specific tasks respectively. As displayed in figure 3, the system consists of three modules, all of them connected but working independently apart from data exchange. In order to sustain a highly effective data processing performance, information is handled mostly on its point of creation, therefore enabling the system to communicate knowledge purposefully avoiding large raw data streams.

The information-marketplace, as an external link of the system to coordinate information supply and demand for all participants of the ACE, provides the robotic system primarily with semantic as well as structural information about the product and regarding the process of disassembly, such as technical documentation, instructions, bill of materials and economic data. The system itself transfers valid process information and the actual condition of parts and components back to the marketplace's database. The common syntax enables bidirectional exchange on a technical level.

Table 2: Requirements of disassembly automation by problem fields

Problem field	Requirements
Process	• High flexibility in disassembly level and methods • Low expenditures for process adaption • Optimization potential and learning capabilities
Product	• Detection and distinction of components and fasteners • Capability of handling a high number of variants • Conservation of knowledge about product and specific processes
Workforce	• System should collaborate with human workers (HRC) • Ability to provide instructions and guidance to workers • Bi-directional communication through GUI • Ability to learn from human behaviour in unclear situations
Information	• Integration into overall information flow of closed loop supply chain • Interoperability standard for information transfer • Utilization of first hands-on advantage • Adaptability to changes of constraints (economic, ecological)
Logistics	• Small lot sizes • Transparency of input and output streams at all times

The main module is the Robot Cognition Processor (RCP), which is the superior control instance of the setup. Synthesizing the different input information-streams, the RCP decides the level of disassembly component-wise by using a deep neural-network classifying the economic and ecological feasibility. An input data stream of 43 important features derived from the data marketplace and optical assessment is therefore pre-processed and used to categorize parts and components eligible for disassembly Furthermore, reinforcement learning optimizes sequencing by processing execution monitoring data and human robot collaboration feedback in a model-free algorithm. Sensory information is provided by the System Perception Unit (SPU). Parts and components are identified, detected and rated for any perceptible damaging such as rust or scratches. The Disassembly Execution Unit (DEU) is responsible for the actual path planning and manipulation in accordance with the disassembly sequence command from the RCP. Acquisition of operating data as well as deployment of instructions for human workers are also part of the module.

The introduction of an AI-enforced disassembly system improves the overall feasibility, thus the attractiveness of recycling to companies can be fostered. The increasing recovery rates of rare materials due to more efficient processes and the potential for 2nd-life applications are beneficial to ecological considerations. An evaluation of a first generic battery dataset was carried out showing the system's ability to reliably classify feasible disassembly cases. The robot cognition unit has been set up as a prototype, carrying out traction battery module disassembly tasks. A detailed description of the setup and evaluations subject to future publications from *Recycling 4.0* project.

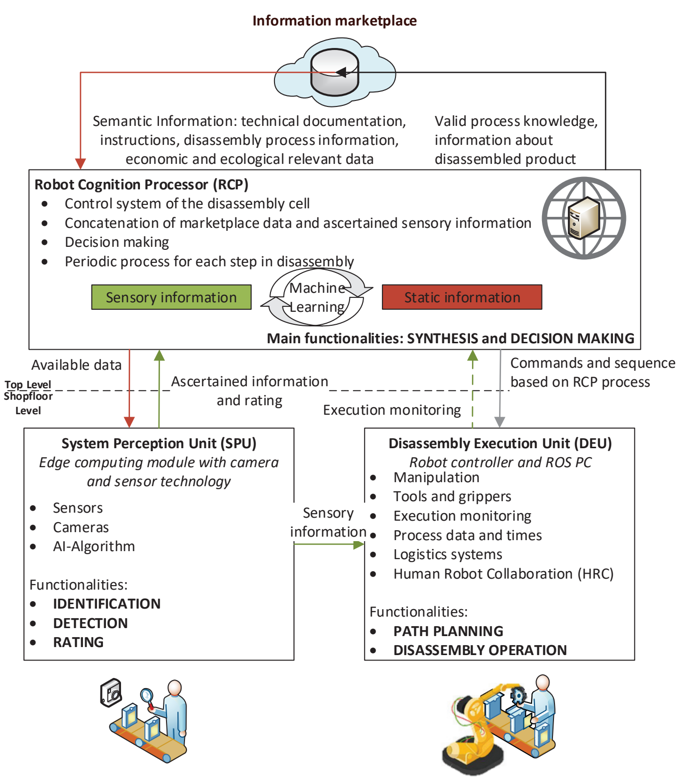

Figure 3: Concept of robot cognition disassembly system

3.5. AN INFORMATION MARKETPLACE AS A BRIDGE FOR THE INFORMATION GAP

According to table 1 and in line with the previous subsections, the ACE based on digitalization and information exchange (see figure 1). A large amount of information is needed and should be linked. However, as already introduced, in many cases there are no incentives to exchange information and there are barriers such as data protection and company secrets. Every stakeholder creates information and data, which could be useful for other stakeholders but is not willing to share them for free. Thus, we propose an information marketplace to bridge the information gap between the different stakeholders. An information marketplace is a variant of an electronic marketplace such as Amazon or eBay, but especially for information and data. By considering data and information as assets, an incentive system can be established which leads to increased information exchange.

Figure 4, shows our information marketplace in the context of the ACE as the central point for the information. The information marketplace offers every stakeholder an easy way to share and sell information. In Figure 4 for example an OEM sells disassembly instructions, to make it easier for a dismantler to automate the dismantling process. In addition, the marketplace is operated by a consortium of all ACE representatives in order to avoid a data monopoly or unilateral advantages. Nevertheless, our architecture also supports all the stakeholders to have a common understanding of the market situation, so that a Pareto optimum can be achieved by creating a "win-win-situation".

However, as shown in table 1, trust and protection of company secrets the main barriers to using an information marketplace. Therefore, we define the following requirements for our recycling information marketplace: ***1.Peer-to-Peer:*** An open peer-to-peer marketplace can be governed and maintained by any parties. The information transfer should take place peer-to-peer i.e. the seller transfers the data to the buyer directly and the information is not stored on the marketplace. ***2.Trustworthy:*** A trustworthy marketplace, is believing that the marketplace which is trusted will do what is expected, on which the other components or stakeholders can rely on and it gives a feeling of security and confidence. ***3.Secure:*** A secure marketplace is free from or cannot be exposed to harm.

But there are also various challenges specific to information and data trading, such as integrity and quality of the data or information, or semantical challenges and the problem of data interoperability. To achieve the Pareto optimum every stakeholder must have the same understanding of information and the possibility to check the information before buying it, which is quite challenging because instead of other products the information can not be retrieved or shown before it is sold. The value of information depends on the content of the information. Accordingly, an already known information has low information content, while unknown information contains a high information content. Furthermore, there are problems on the semantical level, like different namings, which have to be considered in the marketplace. When one stakeholder is searching for data about lithium-ion batteries, but in the offer it called traction batteries, he can maybe not identify his relevant information about the search. Nevertheless, different data formats (data interoperability) are also an obstacle. All these challenges are considered in our architecture and figure 4 shows how to deal with them. For the last challenge, data interoperability, we will show a detailed approach in the following subsection (Connection of the different actors along the supply chain by use of an industrial communication standard). The architecture and the functionalities of the marketplaces is outlined in terms of various services (see figure 4). The buyers and sellers are first registered to the data marketplace with the help of user management service. The offer service lets the seller create an information/data selling offer. Metadata is information/data about the data which lets the seller describe the selling offer more precisely and helps the buy select the offer. The metadata service creates automatic metadata thus creating the integrity of the offer. The data quality check service translates the quality requirements of the buyer into a query language and checks if this the requirements are fulfilled or not. The search and select service let the buyer find and select an offer. Once an offer is selected the service also verifies that the right selected data goes further for the transaction and is not altered. Finally, the payment and transaction service let the buyer pay for the selected offer and the key for the access to the dataset/information. For the final transaction, the access key and the payment enter a smart contract. The smart contract validates the transaction and transfers the data/information to the buyer and the payment to the seller. Smart contracts are self-executing scripts residing on the blockchain. When a preconfigured condition in a smart contract among participating entities is met then the parties involved in a contractual agreement can automatically make payments as per the contract in a transparent manner [41], [42]. A blockchain is essentially a distributed database of records or public ledger of all transactions or digital events that have been executed and shared among participating parties. Each transaction in the public ledger is verified by the consensus of a majority of the participants in the system. And, once entered, the information is immutable [43].

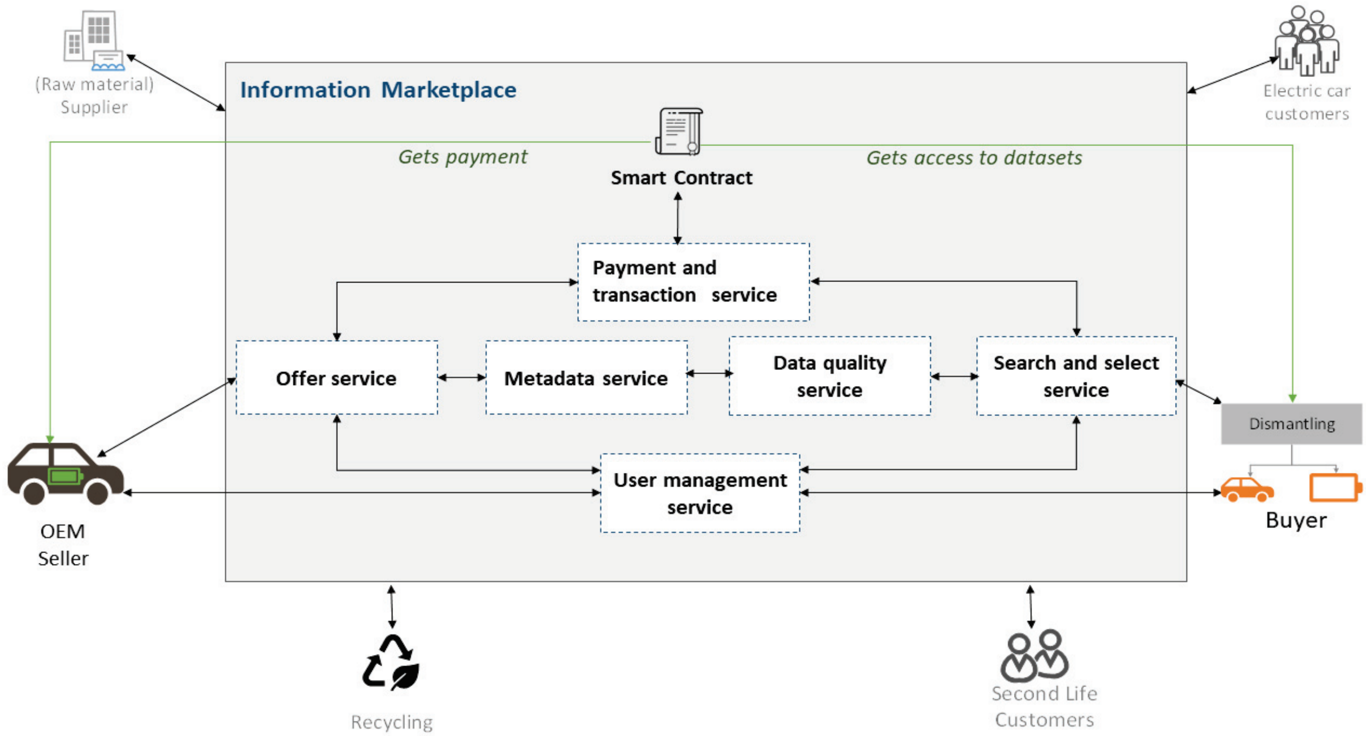

Figure 4: Architecture of the information marketplace

3.6. CONNECTION OF THE DIFFERENT ACTORS ALONG THE SUPPLY CHAIN BY USE OF AN INDUSTRIAL COMMUNICATION STANDARD

All actors need to have access to the previous introduced information marketplace in order to share specific information. The questions are "Which kind of information is shared?" and "How can the information be shared?". Due to computer technologies, the information can exist as digital data. But the problem is, that there are many kinds of different data formats and different communication protocols to transfer the data between devices. Especially the connection of machines different vendors can lead to a problem and to expensive configuration work on interfaces. If all stakeholder and their devices along the supply chain want to communicate with each other, a common interface needs to be used. This chapter introduces the platform-independent standard

OPC Unified Architecture (OPC UA), also known as IEC62541. It is a framework for industrial interoperability and closely linked to the Industry 4.0. The German Electrical and Electronic Manufacturers' Association emphasizes the importance of OPC UA by defining it as criteria for Industry 4.0 products and the Industry 4.0 platform sees the further development of OPC UA "widely supported" [44]. The standard has already arrived in the mind of the automotive industry: "The OPC

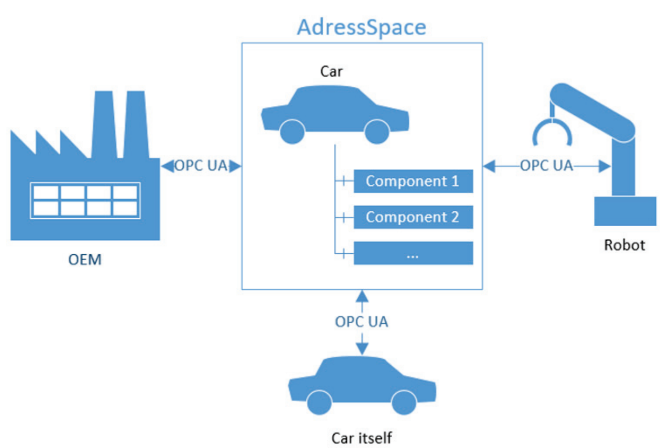

Figure 5: Access to the digital image

UA standard is to be introduced at selected Volkswagen plants by 2022" [45]. Even the beginning of the supply chain, the mining industry, is working on the introduction of OPC UA [46] as well as the "other end" of the supply chain, the waste treatment and recycling sector, is aware of OPC UA [47]. The different sectors along the supply chain are starting to use the same industrial standard for communication. If the OPC UA standard succeeds in the different sectors, it can be used as an overall interface to connect the different devices to the information marketplace and a further step to the ACE through Industry 4.0 technology is made.

Normally, with OPC UA, a device, machine, sensor, etc. is described as a digital twin. For example, the machine is an industrial robot. In this case the digital twin describes the components of the robot, its properties, sensor values and its methods to control the actuators. By following the OPC UA standard it is possible for other devices to get access to this robot. These devices are not only located in the field and control level (where an access is already possible via field busses today) but it is also possible to get access to the robot and read its sensor values from the level of the manufacturing execution system and the level of the enterprise resource planning, e.g. reading the sensor values from another company location with the help of the Internet.

But according to Table 1, the information required by the different stakeholders refer to information and properties about the electric vehicle and its traction battery and the traction battery is different in contrast to a robot in a factory. A new approach and main idea of this chapter is to use OPC UA not only for describing digital twins of devices, robots and machines in a factory. Furthermore, the standard is used to describe the digital twin of a product, in this case an electric vehicle with a traction battery. It describes the whole vehicle and all its components as well as their properties, contained resources, conditions, etc. In the Recycling 4.0 project, the description of the vehicle was transferred to an OPC UA information model. This information model was imported by an OPC UA server. As a result, the digital twin of the electric vehicle and its battery was created.

After the creation by the OPC UA Server, the digital twin of the vehicle gets filled with information. All stakeholder along the supply chain, even the vehicle itself, participate in this process (figure 5). With the help of the information marketplace, the stakeholder along the supply chain can buy a read-access to the OPC UA Server for reading data of the vehicle and its components (e.g. the traction battery) or they can contribute data to the digital twin and earn profit for sharing recycling relevant data.

In the Recycling 4.0 project, the contribution of data by the vehicle was examined in detail. The battery management system is capable in a electric vehicle is capable of calculating the State of Charge (SoC) or the State of Health (SoH) of the electric vehicle battery. This information is of interest to the dismantler of the vehicle at the end of its lifetime, because the information can improve the decision making for the future usage of the electric vehicle battery. With the help of a telemetry unit implementing the OPC UA standard or a smartphone in combination with an On-board diagnostics Bluetooth adapter it is possible to transmit the vehicle data into the digital twin stored on the OPC UA Server. A proof of concept for transferring recycling relevant vehicle data from a vehicle to an OPC UA Server was made in [48].

4 CONCLUSION

In this paper, we presented an integrated approach to handle the upcoming return of EVs and their traction batteries. Our approach to achieve the ACE is to bridge the information gap by using digitalization. In order to manage the integration, we first identified the material, component and information flows and analyzed insufficiencies therein specified. To avoid a Pareto-inefficient state, the exchange of information is essential. Therefore, the exchange has to follow certain rules and meet a certain state of quality. However, as can be seen in Table 1, the different stakeholders may offer or need different information. Nevertheless, important information is not shared due to intellectual property or data protection regulations. Following the SD approach, a material, component, and information flow system will be developed to make the ACE visible, controllable and assessable.

An information marketplace serves as a central point of the information exchange, hence, enabling better information flow and an improved recycling process. The information marketplace not only facilitates buying and selling of information or datasets buts also has a novel architecture which is open, secure and tackles special challenges such as data quality and integrity. The information marketplace will enable a dynamic exchange of information between all stakeholders, even if they do not collaborate or work together. The shown architecture is already prototypically implemented and it could be shown that the described services are technically feasible.

Advanced disassembly systems and automation strategies contribute beneficially to the overall economic and ecologic attractiveness of the recycling process by employing the information flow for AI-enforced processing. Having a common interface for the information marketplace, the disassembly system as well as for the other actors along the closed-loop supply chain will save the user from time-consuming configuration work. Industrial Internet of Things technology, like OPC UA, can help here as a framework for industrial interoperability. Adequate optimization and simulation models enable the economic and efficient realization of the discussed technologies. Furthermore, CLSCM and CLPS are promising ways to overcome the barriers for information sharing. All in all, this approach enables the implementation of an ACE based on improved information generation, exchange and use.

The presented ACE is shown on the example of EOL LIB, although it can be transferred to different (complex) products and processes i.e. electric and electronic devices with high variety in type and condition. Future research demand is necessary concerning the further development of the structures and implementations presented so that the methods and tools can be evaluated holistically and their potential quantified. In addition to the system efficiency, the adaptability and flexibility of the structures must be further developed in order to derive potentials for other product classes.

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