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# END OF LIFE MANAGEMENT OF COMPLEX PRODUCTS IN AN INDUSTRY 4.0 DRIVEN AND CUSTOMER-CENTRIC PARADIGM: A RESEARCH AGENDA

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**ABSTRACT:** Today, developing tools and methods for advanced management of the complex product through their life cycle in the new paradigms of sustainability, manufacturing, and information technology is essential. The new trends in manufacturing, information technology, and logistics influence the circular economy. The long-term goal is to provide the recycling companies, manufacturers, and the other key players in the life cycle management of the complex products with tools and methods for analyzing the implications of these new trends and support the robust circular economy. In this article, the influence of Industry 4.0 and the customer-centric paradigm on the management of the complex products at the EoL is discussed. The examples of the applications in End of Life (EoL) aircraft treatment are also provided to shed light on the discussion. This perspective article aims to outline the research agenda that addresses some of the research questions in the current and future of advanced management of the complex products at the end of life.

**KEYWORDS:** *Circular economy, Industry 4.0, Customer-centric paradigm, EoL product management, research agenda*

## 1 INTRODUCTION

Today, more consumers around the world consider the environmental and social responsibility of producers and take into account the sustainability in their purchasing decision-making. In the new paradigm of sustainability, the circular economy is defined as “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, and repair, reuse, remanufacturing, refurbishing, and recycling” (Geissdoerfer, 2017, P.759). This proactive approach to sustainability should be integrated into new paradigms in manufacturing, emerging technologies, and the new trends in business. The emerging trends affect the circular economy and life cycle modeling. There are some significant trends and challenging areas: The global peak population and evolving global landscape as well as an emerging technology. The growing population changes the rate of product consumption and the uncertainty in supply and demand for recycled materials. It triggers the new federal or provincial regulations for end of life products treatment and cradle to grave practices. Evolving global context influence the complexity of the product recovery network, the relationship among key players, and life cycle modeling. Furthermore, consumers need more customized products. These trends cause growing open-architecture and complex consumer products as well as the need for developing the novel methods and tools for design and material chain strategy. The costs, engineering aspects, subsystems, networks, and constructs define the complexity of the products. Moreover, the interaction between design features, construction, technology, suppliers, and legislation affect the

degree of complexity. Disruptive technologies such as Industry 4.0, Internet of things, big data, and 3D printing change paradigm in the supply chain context. The new paradigm of Industry 4.0 affects the green supply chain includes green design, green manufacturing and remanufacturing, reverse logistics, and waste management. Examination and adoption of the Internet of things (IoT) and big data analytics in the product recovery network and the role of embedded real-time data are essential. The opportunities and challenges for designing the product recovery networks and assessing the dynamic interactions among entities could reveal the creating value through these new technologies. In this article, the implications of Industry 4.0 and the customer-centric paradigm on the management of the complex products at EoL are discussed. The contribution of this study is two folds: first, it summarizes the state of the art of the EoL products management in the context of Industry 4.0 and considering the new trends in product design. Second, it provides a research agenda in the field with some examples from the case of EoL aircraft. The rest of the paper is organized as follows: Section 2 discusses the different types of products and the impacts of the evolution in product development on the complexity of EoL management. Section 3 reviews the implications of Industry 4.0 with some examples in data analytics deployment, virtual reality, and distributed network in the case of EoL aircraft and the perspectives of future research. Finally, section 4 concludes with some remarks.

## 2 DIFFERENT TYPES OF PRODUCTS AND LIFE CYCLE CONSIDERATION

The complex products need a systematic approach to integrate the ecological concept into the product design phase. This systematic approach requires considering technical, functional, aesthetic, and environmental data

simultaneously. For these complex products, analyzing ecoefficiency data for all modules, components, and subparts is not a simple task, and need to develop tools and techniques for data exploration (Keivanpour et al., 2018). Favi et al. (2019) developed a tool for the design of the disassembling of mechatronic products. The authors proposed improving feedbacks from tools for designers, integrating of tools into eco knowledge management systems, and using circular economy indicators for assessing the sustainability of different scenarios for EoL treatment as the research gaps in design for environment tools. Zhang et al., (2017) studied the role of big data in clean management and the manufacturing of complex products. The authors emphasized that converting the results of big data analytics into easily comprehensible forms via visualization and extracting hidden knowledge and rules from data mining for optimizing life cycle management of the complex product for the decision-making process is essential and has not been investigated by scholars. Open architecture products are a new class of products with a fixed platform and modules that will be added in later stages based on customers' preferences. These products have the potential to become a large share of the economy in Europe, North America, and large countries in Asia (Koren et al., 2013). The platforms are produced by manufacturers and many small companies will be established to produce the modules for a variety of customers' choices. For a complex product, the manufacturer is responsible for design approval and sustainability of the final product. However, the small companies and some times customers interfere in product design and they do not have access to the advanced design tools.

The role of customers is changed in the new paradigm of manufacturing. They could involve in design and contribute to the lifecycle of the products. Mass individualization provides opportunities for small companies to contribute to the design and manufacturing of the products. This paradigm causes multiple companies and buyers involved in product design. We will have more open platform products that facilitate the integration of computers embedded systems and mechanical modules. Koren et al. (2013) defined the open architecture product as a platform that allows the integration of different modules from different manufacturers to meeting the customer requirements. Some studies discuss how open-architecture products influence the design and manufacturing process. However, the impacts on other stages of the life cycle of the product and the EoL phase have not received much attention in the literature. Zhang et al. (2015) provided a comparison between different types of products to highlight the characteristics of the open-architecture products. The authors divided the product type into five categories: Mass-produced products, mass-customized products, reconfigurable products, upgradeable products, and open-architecture products. Here, the same classification is used to clarify the EoL challenges for each product type. For mass-produced products, there is not any option at purchasing and during the use

phase. The standardized nature of the products could facilitate reusing and recycling. Hence, the standard process for the EoL system could be designed. For the EoL management, the high degree of automation could be applied as there is not any change during the life cycle of the product. The eco-design could be done by the manufacturer easily. For mass customized products, there are options for customers in the purchasing stage. However, there are not any modifications in the operation phase or adding the parts or modules later after purchasing. As the options are available in the design stage, manufacturers can integrate the eco-design techniques for different options of the product. For reconfigurable and upgradeable products, recycling would be more difficult as the changes and modifications would happen in the operation stage too. Though, the manufacturer can still integrate sustainability into the design stage and for the different options and modules. For open-architecture products, the modifications in the product modules could happen at the design, gate, and operation stage. Hence, considering the involvement of different manufacturers for known or unknown modules, the application of the 3R approach (reducing, reusing, and recycling) could be challenging.

**Table 1: The complexities of 3R approaches application based on the product types**

Types of the products	Difficulties in applying the 3R approach (L: Low, M: Medium, H: High)		
	Reducing	Reusing	Recycling
Mass-produced product	L	L	L
Mass customized product	M	L	L
Reconfigurable product	L	M	M
Upgradeable product	L	H	H
Open architecture products	H	H	H

Table 1 shows the level of complexity in applying the 3R approach for different types of products.

One challenge in reusing is the complexity of disassembling operation. Here, the complexity of disassembling operation in open-architecture products is explained.

Figure 1 shows an example of an open architecture product with two known modules and one unknown module.

Tseng et al. (2010) proposed a disassembly-oriented methodology for product module items. The first step is describing the physical structure of the product using the liaison graph. This graph is based on the parts of each module as shown in figure 1.

The key element in finding the optimized sequence of disassembling is calculating the cost of disassembling, the value from the recovered parts and materials. For the cost of disassembly, the efforts based on unfastening action or destructive action, and the complexity of the process, the time and labor costs should be considered for each module. In the case of open-architecture products, the cost should be estimated based on the known and unknown modules. For the unknown module, the complexity of unfastening action or destructive action

could be increased as the result of lack of information or lack of the effort of the manufacturer for the design for disassembling. This complexity could add the disassembling time and subsequently the cost. Usually, the genetic algorithm could be used for the decomposition of the product into basic modules. The algorithm should be adapted in the case of open-architecture products to maximize the recovered value considering the unknown modules' contact type, combination type, tool, and accessed direction.

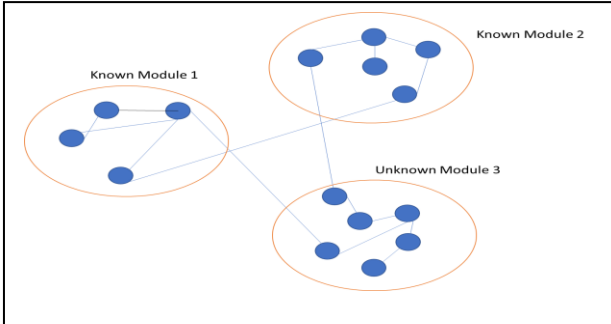


Figure 1: Example of an open-architecture Product (liaison graph)

### 3 INDUSTRY 4.0 AND IMPLICATIONS IN EOL MANAGEMENT

The implication of Industry 4.0 paradigm on the life cycle of the products is a fresh research theme. More empirical studies are required to assess the challenges and discuss the application perspectives. Extensive information should be analyzed to reduce the uncertainties in the different sub-processes of treatment. As disassembly/dismantling operations are labor-intensive tasks, real-time scheduling by providing accurate information on treatment operation resources, tools breakdowns, and any changes in the planning process are critical. Industry 4.0 and data analytics provide the required information and reduce the uncertainties in terms of the value extracted from recovered parts and material and total costs of the operation. Rahman et al. (2020) proposed “EoL 4.0” for real-time data exchange among the key players and implementing analytical capabilities of Industry 4.0 for maximizing the value from EoL products. The challenges of EoL systems in the new paradigm of Industry 4.0 is shown in figure 2.

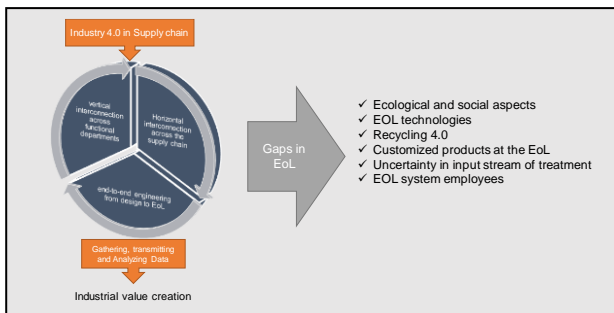


Figure 2: The challenges in the treatment of the EoL products in Industry 4.0 paradigm (source of data Rahman et al.,2020)

Rosa et al., (2020) also provided a synthesis of the literature of circular economy in the context of Industry 4.0. According to these authors, the published case studies are related to China, the US, and Europe. The topics of published papers are more focused on life cycle management, supply chain management, resource efficiency, smart services, and the adoption of the new business models. Hence, more research should be performed in other countries and focusing on topics such as Dismantling 4.0, reusing, and recycling 4.0 as well as remanufacturing 4.0. Figures 3 and 4 highlighted these gaps. In the following sub-sections, the implications of data analytics deployment, virtual reality, and blockchain with perspectives of the application in the case of EoL aircraft treatment are discussed.



Figure 3: The publishing nations of the case studies related to implications of Industry 4.0 in the circular economy (source of data: Rosa et al.,2020)



Figure 4: The gaps in the topics of the articles( Disassembling 4.0, Reusing 4.0, recycling 4.0, and remanufacturing 4.0 are the research areas that needed more attention (Source of data: Rosa et al., 2020)

### 3.1 Data analytics Deployment

Keivanpour et al., (2017) developed an interactive interface for dismantling operations options, partner selections, capacity planning, collaboration choices, distribution networks, and performance trade-off to provide an expert system for the recovery of EoL aircraft. Tractability of the critical parts and materials, particularly the hazardous material, is an essential implication of RFID (Radio Frequency Identification) in the treatment process. Documentation and quality assurance of the recovered parts could be performed via database management systems and business intelligence. Simić and Dimitrijević (2010) discussed the advantages of using RFID in the context of the End of Life vehicle closed supply chain. The authors stressed the role of RFID and management information systems in data sharing for dismantling and design, life cycle data management, and product information management. Keivanpour et al. (2018) discussed the perspective of the application of big data analytics in the treatment of EoL aircraft. The secondary data from disassembling and dismantling of the horizontal stabilizer is used to illustrate the implication of knowledge management systems in the treatment process of EoL aircraft.

Poschmann et al. (2020) reviewed the studies that addressed the application of robotic in disassembling operation. The authors discussed that the application of autonomous robot cells and artificial intelligence (AI) for optimization of the disassembly sequences is the evidence of automatic robotic disassembly. Kerin and Pham (2019) mentioned two applications of Industry 4.0 in the disassembling process including simulation and models for virtual disassembly and smart robotic disassembly with real-time data application. Parsa and Saadat (2019) applied a hybrid optimization model for optimizing the disassembling sequences using multiple data fields.

EoL aircraft management is a multi-aspect operation management problem that includes several strategic, tactical, and operational decisions. Advanced data mining could improve decision making in different phases of EoL aircraft treatment. For the successful operation of re-used and remanufactured parts and components, the reliability of the components, ease of disassembling, inspection, cleaning, and maintenance data should be considered. This data should be shared via an information system between key players: manufacturer for design features, the operator for maintenance and condition monitoring, and the history of failures and dismantling or recycling agents for the treatment operation (Keivanpour et al., 2018). Databases play an important role in data analytics. Databases can aid in the integration of the data during the life cycle of the product. Now, EoL aircraft enterprises use different databases for inventory management, sales, and marketing of the recovered parts, processing manufacturer's data and maintenance records. An integrated database management system should be developed to facilitate the management of different data in all sub-processes of treatment. For

example, data of material scarcity, recyclability, disassembly time, disassembly outcomes, and condition monitoring including vibration data oil analysis, loading/speed, moisture/humidity, and temperature/pressure should be analyzed. Mean-time between failures and operational performance data will be used for the estimation of the remaining useful life of the parts. The operation data including the dismantling time, labor records, the inventory of required tools and equipment are essential for close monitoring of dismantling time and finding bottlenecks in the treatment process. Moreover, this databased could be integrated with the data mining module for lean management of the EoL treatment operation. As multiple operational information systems should support the different sub-processes of treatment operation, the repository of all historical data regarding modules and components should be tracked and the continuing stream of real-time data during dismantling and disassembling phases should be assessed. Data warehouse creates the opportunity for analyzing the vast and multidimensional data. The different disassembling and dismantling strategies should be assessed based on the types of material, recyclability, replicability, and material scarcity. For data mining purposes, first, an adaptive neuro-fuzzy inference system considering a large amount of stochastic (linear and non-linear) data in the sub-processes of treatment could be used. Then, a fuzzy logic model will be applied to maximize the value recovery by analyzing the different scenarios of dismantling and recycling based on the waste hierarchy approach.

### 3.2 Virtual reality for integrated and sustainable recovery

EoL aircraft recycling is a new challenge in the aviation industry and few scholars addressed this subject in detail via real case studies (e.g. Sainte-Beuve, 2012; Sabaghi et al., 2015; Zahedi, 2016 and Keivanpour et al., 2017). For the EoL aircraft, access to advanced optimization tools and specialized machinery for reducing dismantling time and decreasing the waste of operation is critical. The recycling of the skeleton is not a profitable operation like removing parts and components; however, applying smart sorting solutions could increase the benefits (Sainte-Beuve, 2012). It requires the multidimensional assessment including time, difficulty, and material compatibility of the parts or modules in disassembling strategies. Hence, the use of a disassembly database including unfastening or cutting time, effort, the number of fasteners, geometrical specifications, maintenance manual, and structural repair manual, CAD (Computer-aided drafting) data, and parts database is essential (Zahedi, 2016). The digital twin provides a dynamic digital profile of a physical object and integrates 3D model, historical and real-time monitoring of the object behavior for optimizing the virtual reality. Recently, it has been received much attention in design, production, operation, and maintenance (e.g. Tao et al., 2019; Liu et al., 2019; Min et al., 2019). The application of digital twins at the



EoL is ignored in the research like the other aspects of Industry 4.0 at the EoL (Rahman et al., 2020). Few studies mentioned the perspectives of the applications for recycling and remanufacturing (e.g. Wang & Wang, 2019 and Wang et al., 2019). However, the application as the strategic tool for EoL management of complex products is not addressed in the literature. Mapping the skeleton of the aircraft based on the material zones considering the complexity of the material mix is vital for optimizing the dismantling and cutting process. The digital twin could provide a digital mapping capability enabled with multidimensional data processing, optimization, visualization, intelligent decision making for delivering the optimum dismantling solutions. The essence of the digital twin model is comparing the different dismantling and disassembling strategies with the aggregation of several dispersed databases, data analytics, and visualization dashboard. These databases include aircraft manufacturers' data, OEM data, maintenance, and operation historical data, and the second-hand parts market dataset. Data analytics aids in optimizing the disassembling sequences and smart cutting considering geometric improvement and edge preparation. For example, one scenario for dismantling is not removing rivets that are shared between components with similar materials. The analytical tool aid developing iterative models for finding reverts and comparing different strategies. More visibility regarding addressing the hazardous material and substances of concerns will be provided. The different disassembling scenarios will be simulated and visualized in an interactive decision-making dashboard for elaborating the process and giving insights. This architecture provides the flexibility of the data processing and integrates the massive data for sustainable solutions considering the uncertainties and complex nature of the EoL aircraft recycling problem.

### 3.3 Blockchain for tracing the recovered parts

There are some challenges in the management of the recovered parts from the EoL complex products such as aircraft. According to the International Air Transport Association (IATA), all the changes in the part movement should be tracked during the lifecycle of the products. Rajkov (2018) discussed the complexities of the aircraft supply chain due to the aircraft configuration, the multi-levels and global supply chain, the difficulties in spare part management, and the communication. Furthermore, using IoT and RFID has some challenges including energy consumption, communication, synchronization, and security. Hence, assessing the business model for the application of blockchain technology in tracing and tracking the recovered parts and providing a use case could be an interesting research area. Rajkov (2018) provided a SWOT analysis for the application of blockchain technology in the spare part management in the airline industry. Evaluating the role of the EoL initiative in an inter-organizational digital distributed network is critical.

## 4 DISCUSSION AND CONCLUSION

The important challenges in the circularity of utilized materials are time-tested processes of reuse, recovery, and recycling that reinforce circular economy initiatives (Tam et al., 2019). Designing closed material chains for strategic and valuable materials will be more essential than the weight percentage target of recovered material (Knieke et al., 2019). The new technologies in vehicles and lightweight constructions require novel treatment processes and strategies for EoL of complex products. The proposed research agenda will provide an essential contribution to the field of the operationalization of sustainable development by developing innovative tools and decision support systems considering the impacts of new business trends and cyber-physical technologies on the circular economy. The management of the complex products in the circular economy is a dynamics and transdisciplinarity research agenda and it facilitates and expedites knowledge diffusion among researchers, practitioners, and policymakers. Moreover, it includes opportunities for extensive training high-quality personnel, and engineers in the field.

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