End-of-Life in industry 4.0: Ignored as before?

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Industry 4.0, indicating a fourth industrial revolution, is based on three basic forms of integration through digital technologies: Horizontal interconnection across the supply chain, vertical interconnection across functional departments, and end-to-end engineering from product development to recycling. By gathering, transmitting, and analyzing data throughout these three forms of integration, several benefits are anticipated for industrial value creation. Relating to the Triple Bottom Line of sustainability, economic, ecological, and social benefits are targeted by Industry 4.0. Extant research on Industry 4.0 has begun to investigate the technological developments from an economic perspective, while the understanding of ecological and social aspects of Industry 4.0 is considerably less understood. Further, entire supply chains, or end-to-end processes have been considered less so far, despite necessary for unlocking the entire benefits of Industry 4.0, especially in an ecological and social regard. Developing the concept of Industry 4.0 towards the idea of a Circular Economy requires to better consider downstream aspects, while benefits are mostly investigated for upstream processes so far, especially towards the End-of-Life (EOL) and recycling of products (Birkel et al., 2019; de Sousa Jabbour et al., 2018; Müller and Voigt, 2018).

In general, EOL technologies tend to be underdeveloped while relying on basic technologies, far inferior to the contemporary technology used in the upstream industries (Reck and Graedel, 2012). The present articles therefore attempt to shed light whether this backlog is going to persist in Industry 4.0 as well.

As opposed to a large body of extant literature on Industry 4.0, only very few articles appeared that broadly fall into EOL areas, analyzing the connection between Industry 4.0 and Circular Economy. This is a significant gap that needs to address by researchers, policymakers and managers.

There is little research associated to ‘Recycling 4.0’. Examples include one project in the European Union, named 'Recycling 4.0' and the other two are recycling companies that implemented a relatively higher degree of automation for the recycling of specific materials or products. For instance, the focus of the project in the European union is the use of big data at the EOL vehicle systems and develop technologies that can successfully build an online marketplace so that actors across the globe can exchange trade and supply chain information, based on real-time data transfer. While this indicates that some efforts towards upgrading EOL in parallel to Industry 4.0, more focus regarding their performances, challenges, and business communication pattern is crucial (Tseng et al., 2018).

While terms such as ‘smart recycling’ or ‘recycling 4.0’ are used, we propose that EOL 4.0 is more representative in that, real-time data exchange among supply chains is encompassed while using data transmission and analysis capabilities within the concept of Industry 4.0 (beyond automation) and implementing sophisticated value retention options in EOL (beyond recycling). EOL 4.0 can, therefore, be defined as an advanced EOL system that uses approaches and technologies of the upstream processes in Industry 4.0 and maintains a real-time data synergy with intelligent products.

Industry 4.0 builds on high collaboration among the supply chains in terms of real-time data exchange, cloud-based information access and increased customization of products (‘lot size one’). This includes, for example using additive manufacturing technologies, leading to challenges referring to recycling and reuse of more customized products (Birkel et al., 2019). This quick and customer appreciated products will be designed in a different manner from existing products and processes. Therefore, EOL 4.0 may have to face a different input (product to be recycled often gets fatigued, bent, twisted and distorted, unlike upstream manufacturing) - an additional challenge that may not allow outright use of the Industry 4.0 technologies in the recycling systems and requires further research and innovation activities.

Additionally, a real interest and partnership of the upstream industry 4.0 pioneers is necessary so that development of EOL 4.0 is coordinated and key challenges are identified and addressed at the outset of the Industry 4.0 maturation.

Socio-economic repercussions are also expected to be different from upstream processes discussed for Industry 4.0. For example, EOL system employs a predominantly higher number of low skilled labor, compared to the upstream manufacturers where the skill level of the employees is expected to be relatively advanced. In EOL 4.0 scenario, the low skilled

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Table 1
EOL level digitalization technologies and issues.

Level	Steps	Possible technologies/assessments	Possible issues
Technical	Manufacturing	Product information reservoir	Data privacy and business communication
	Use	Dynamic feature tracker	Communicating information to EOL managers
	Disposal	EOL signaling	Consumer signal comprehension
	Collection	Smart collection box	Signal comprehension
	Transportation	–	–
	Sorting	Sensor based recognition	Machine vs Human decision making
	Dismantling	Robots, cobots	Parameter setting and talent human resources
	Remanufacturing/reuse (product/component/material)	Cyber physical systems, robot, feature readers and decision makers	Appropriate human resources
Social	Labor force	Labor training and skill development	Reinitiate training modules
Regional	Waste trade	–	Regional Inequality
Assessment level	–	Circularity assessment, Environmental assessment and Economic assessment	Human resources, rebound effect
	Technology readiness	Upstream and downstream technology indexing	Comparison and viability studies

workforce would largely be redundant as training the low skilled human resources to adapt with digitalized machineries is expected to be more problematic. Further, it might be the case that EOL 4.0 will be highly implemented in western countries, which may lead to minimize waste recycling in developing countries.

Like in Industry 4.0 research areas, dominant EOL 4.0 research areas would be as follows: core technology development and its related implementation challenges; organizational and management readiness; communication pattern of human and robotics; security and reliability of the intelligent systems; supply chain management; issues related to data communication, reliability and exchange. In particular, research on evaluating and monitoring the digitalization level (and rate of progress) of the upstream industry, developing tools to track product nature and material content, anticipating material recyclability in digitalized products and predicting the security challenges of the increased automation is required (Table 1).

EOL 4.0 can be introduced in two phases: a knowledge phase, and an implementation phase. In knowledge phase, focus should be given on the identification of the opportunities and challenges of the core technologies, nature of recyclable inputs and quality of recyclate outputs of Industry 4.0 waste streams. Best practices of the successful introduction are also vital, based on empirical evidence and application examples. In the implementation phase, technology optimization processes (e.g., technological assessment, economic and environmental impacts) should be initiated. In addition, organizations must clearly integrate the requirements of EOL in the overall Industry 4.0 strategy. Further, the connection of EOL 4.0 with Industry 4.0 implementation processes must be ensured through better aligning investments and adjusting compound effects of upstream and downstream processes in industrial value creation.

Integrating EOL in Industry 4.0 implementation phase would minimize the dichotomy between upstream manufacturing and downstream processing. It is expected that the industry 4.0 will bring profound changes in how the existing industry organizes human and environmental systems, with similar effect anticipated in the EOL systems. In this case, Industry 4.0 approaches need to more seriously consider EOL in order to enable benefits for the environment and society. Integrating EOL in Industry 4.0 is required in order to approach the full benefits of Industry 4.0, especially in an ecological and social regard.

Declaration of Competing Interest

All authors declare no conflict of interest.

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