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Multiple Life Cycles in the Circular Economy: Making it happen with enabling technologies of IR4.0

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Abstract. The Circular Economy model demanded industries to consider restorative and regenerative strategies in developing products in order to mitigate the adverse impact of their consumption and production to the environment. These products which are intended to be recovered for reuse as many times through value added recovery strategies are referred to as multiple life cycle products. Today, the implementation of multiple life cycles is still hampered by several issues including poor products design, inefficient take back and poor quality of cores, as well as sociotechnical issues which could be mitigated through effective sharing of data, information and knowledge. This paper discussed end of life strategies, industrial case examples and current challenges for the implementation of multiple life cycles. The advent of enabling technologies of IR4.0 which supports digitalisation, should be able to assist in efficient handling of vast data, information and knowledge throughout the multiple life cycles of products. The paper concludes with some of the IR4.0 technologies which could be deployed to address pressing issues in the recovery of multiple life cycle products in order for the manufacturers, suppliers and society to rapidly move forward to a more sustainable environment in the Circular Economy.
Keywords: Circular Economy, Industry 4.0, digitalization, multiple life cycles, remanufacturing

1. Introduction

The world economy is now set to replace the take-make-dispose linear pattern of consumption and production to the Circular Economy (CE) in which the value of products, materials and resources is maintained in the economy as long as possible [1]. The Ellen MacArthur Foundation has defined CE as an industrial system that is restorative or regenerative by intentions and design [2]:

> "*A circular economy is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, and aims for the elimination of waste through the superior design of materials, products and production systems.*"

A study on the growth of CE and its impact on the UK labor market noted that one route to improving resource efficiency is to develop CE as it enables products and resources to be in use for as long as possible through recovery, reuse, repair, remanufacturing, and recycling [3]. Today, CE is not an option but a requirement for continued economic prosperity and ecological balance [4]. The McKinsey Quarterly Report No. 1 as shown in figure 1, clearly depicts the close-loop strategies for treating biological and technical materials.

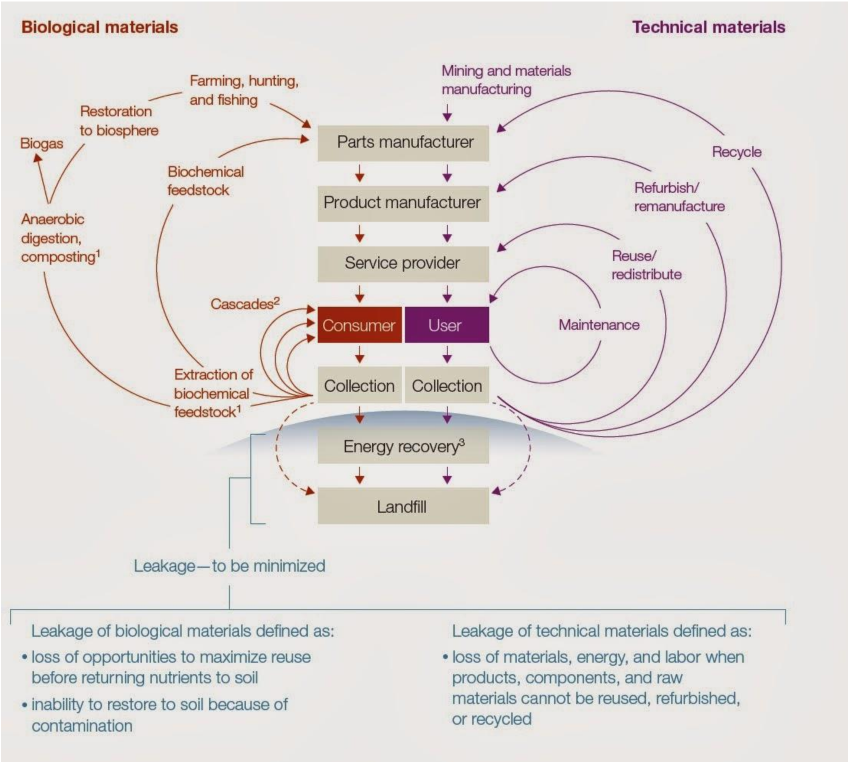


Figure 1. Shaping the Future of Manufacturing [5]

The World Economic Forum outlined a few simple principles of CE which includes the following [6]:

- Waste does not exist: products are designed and optimised for a cycle of disassembly and reuse.
- Consumables or products of biological ingredients can safely be returned to the biosphere, either directly or in a cascade of consecutive uses, while durables such as engines or computers are designed for reuse, and products subject to rapid technological advance are designed for upgrade.
- Durable products are leased, rented or shared wherever possible. Otherwise, incentives or agreements must be in place to ensure the return and thereafter their recovery.

2. Product Life Cycle Extension through Value Added and Resource Efficient Strategies

Developing products for an extended lifetime which is the tenet of CE, is referred to as multiple life cycle products in life cycle thinking. Multiple reuse, remanufacturing, or a combination of recycling, reuse and remanufacturing enables products to have multiple life cycles. However, the implementation of multiple life cycles require several aspects of the product's design to be taken into consideration at the early design stage such as durability, ease of disassembly and reassembly, modularity, accessibility, simplicity, utilisation of standard parts and ease of maintenance [7]. Designing products for multiple life cycles helps to maximise the utility of resources used in developing a product by integrating features that can help to prolong the lifetime of the product [8]. Some of the strategies for multiple life cycles (as depicted in figure 1) are explained briefly as follows:

2.1. Remanufacturing

Remanufacturing is more resource efficient than recycling and other end of life recovery strategies, as it retains durable cores in the subsequent life cycles, hence reducing the need to manufacture new components every time. Since remanufacturing retains the geometric shape of products, it preserves the materials and added value embedded in the original products [9]. The remanufacturing process involves disassembly, cleaning, inspection, restoration, reassembly and finally testing, after which the remanufactured product is given a matching warranty. A generic representation of the remanufacturing process is shown in figure 2.

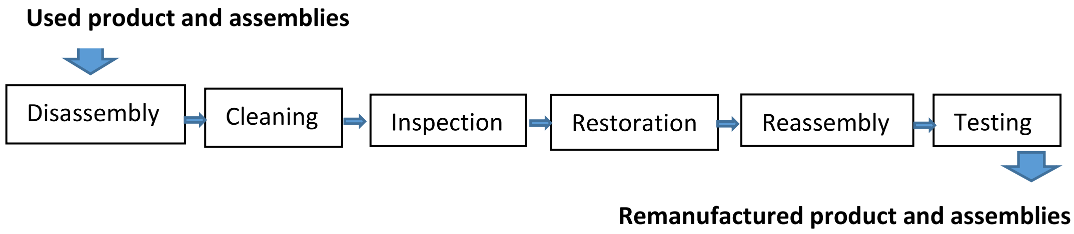


Figure 2. A generic remanufacturing process.

Since remanufacturing does not involve actual production of new products, the process demands very little raw material, energy, and other production inputs thus reducing the environmental impact of production. To date the remanufacturing sectors include aerospace, automotive, catering & food, construction, ICT equipment, industrial tooling, ink & toner cartridges, lifting & handling equipment, medical, precision & optical equipment, off-road equipment, office furniture, pumps & compressors, rail industry, textiles and white goods.

2.2. Product Upgrades

Upgrade is defined as the process that involves the functional enrichment of a product [10]. Modular upgradability is a strategy for improving the environmental performance since it allows for an independent replacement of improving subsystems, instead of replacing the entire product [11]. By applying modular design in multiple life cycle products, manufacturers are able to update the modular structures of their products through remanufacturing [12] and thus, improve the dynamic performance and capabilities of the product. Design for upgradability in multiple life cycle products enables the upgrading of features that will provide significant improvements to a product and also to help prolong the product lifetime. Upgradability is one of the major criteria in designing a product based on the life cycle thinking which not only supports product sustainability but also service life extension, which is the basis for product service systems [13].

2.3. Maintenance

Preventive and predictive maintenance are among proactive strategies in extending the useful life of a product or systems. These strategies influence products` life cycle and reliability, hence their availability [14].

3. Industrial case examples of operational changes for CE

Case Study 1: Renault, a French automotive manufacturer [6]

- *Redesign and Remanufacturing*- reengineers different mechanical subassemblies, from water pumps to engines, to be sold at 50 to 70% of their original price, with a one-year warranty. The company also redesigns components (such as gearboxes) to increase the reuse ratio and make sorting easier by standardizing components. Renault has achieved reductions of 80% for energy, 88% for water and 77% for waste from remanufacturing rather than making new components.

- *Working with recyclers and waste management companies* - to incorporate end-of-life expertise upfront into product design and provide access to a steady supply of components and materials.
- *Access-over-ownership business model*. Renault became the first car maker to lease batteries for electric cars to help retain the residual value of electric vehicles (to encourage higher consumption) and make batteries fully traceable, ensuring a high collection rate for closed-loop reengineering or recycling.

Case study 2: Caterpillar Inc., manufacturer of heavy machineries [15]
Caterpillar remanufactures complex, durable components like gearboxes, drivetrains and brakes. The strategy in Caterpillar is to create a product that is intended to be remanufactured a number of times for use in multiple life cycles.

- Innovation in remanufacturing- In the past, an engine block is remanufactured by re-boring the engine cylinder and using a larger piston. However, this can only be done up to three times after which the quality of the product will be affected. To overcome the issue and to ensure a longer useful life of the core components, an innovation was introduced by having a removable sleeve in the cylinder bore. Upon recovery, this material is removed and replaced to return the engine to as-new performance.
- Condition monitoring- From the regular and simplified maintenance process between dealer and customer, Caterpillar has now embarked on the use of digital technology to add a `Pdt Link` service to units in the field for e.g. fuel level and potential risks.

Case study 3: Ricoh provider of managed document services, production printing, office solutions and IT services [15]

- Design for recycling and reuse- Copiers and printers are designed and manufactured such that they can be recycled or reused. In addition to remanufacturing, the company refurbishes and upgrades pre-owned machines. For products that cannot be remanufactured, refurbished, or upgraded, Ricoh harvests the components and recycles materials at local facilities and also in Asia for use in new component production.

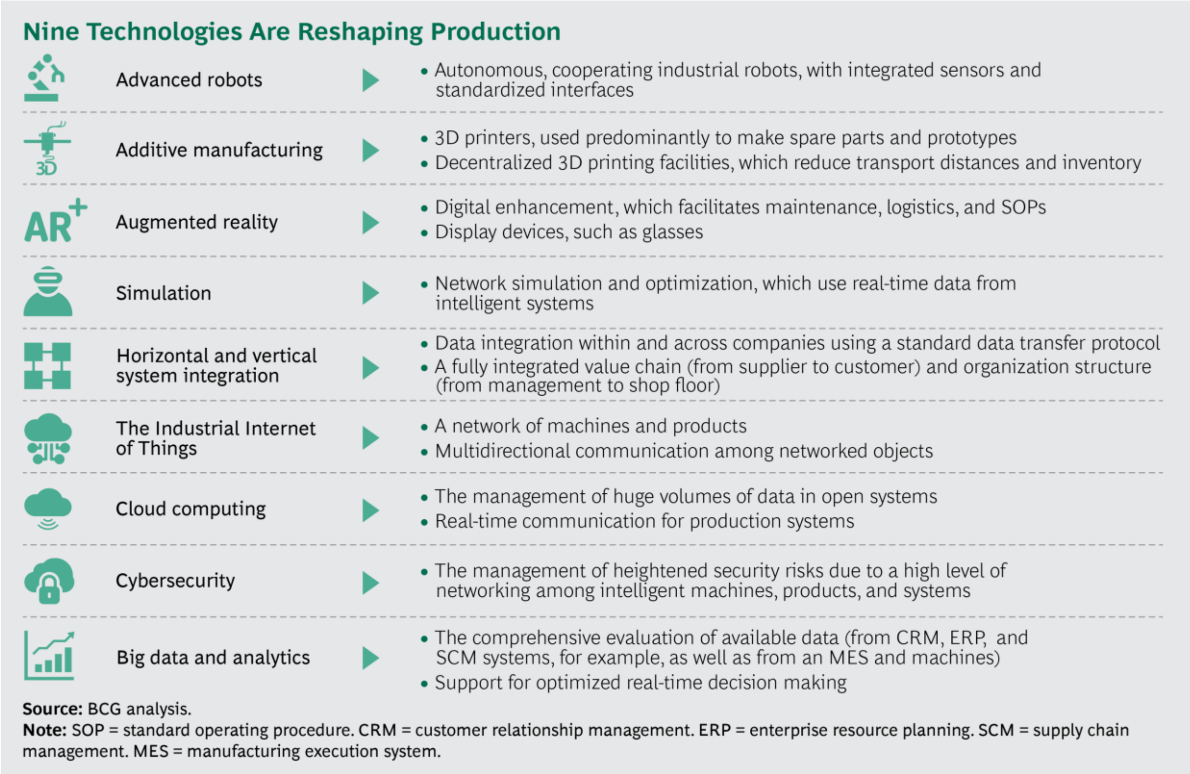
Case Study 4: Philips lighting as a service [15]

- Retaining ownership- In order to enhance collection and recycling of lighting equipment, Philips has started to sell lighting as a service. Philips says they can reach more customers if they retain ownership of the lighting equipment as customers don't have to pay high upfront costs and Philips ensures the sound environmental management of end-of-life lighting equipment.

4. Enabling technologies supporting multiple life cycle products

Over the years, ICT and enabling technologies have played a key role in industrialisation. From supporting virtual organisations in sharing knowledge and competencies in the nineties, the role of enabling technologies are getting more significant in the CE. From tracking and locating materials, products and other form of resources for the reverse logistics, it enables the mining of large data and information to be shared. Figure 3 outlined the nine enabling technologies of IR4.0 that are seen to be reshaping production and the economy in general [16].

The advent of digital technologies such as Internet of Things (IoT), 3D printing, Big Data analytics, virtual and augmented reality, etc. are reshaping the industry in line with the CE model. The potentials of these enabling technologies have largely been reported which includes Augmented-reality-based systems that support a variety of services, such as selecting parts in a warehouse and sending repair instructions over mobile devices; Cybersecurity which provides secure, reliable communications as well as sophisticated identity and access management of machines and users through increased connectivity and use of standard communications protocols; Simulations for leveraging real-time data and mirror the physical world in a virtual model, which can include machines, products, and humans; Horizontal and Vertical Systems Integration which provides companies, departments, functions, and capabilities with cohesiveness, as cross-company, universal data-integration networks evolve and enable truly automated value chains [17].



Nine Technologies Are Reshaping Production

Advanced robots	• Autonomous, cooperating industrial robots, with integrated sensors and standardized interfaces
Additive manufacturing	• 3D printers, used predominantly to make spare parts and prototypes • Decentralized 3D printing facilities, which reduce transport distances and inventory
Augmented reality	• Digital enhancement, which facilitates maintenance, logistics, and SOPs • Display devices, such as glasses
Simulation	• Network simulation and optimization, which use real-time data from intelligent systems
Horizontal and vertical system integration	• Data integration within and across companies using a standard data transfer protocol • A fully integrated value chain (from supplier to customer) and organization structure (from management to shop floor)
The Industrial Internet of Things	• A network of machines and products • Multidirectional communication among networked objects
Cloud computing	• The management of huge volumes of data in open systems • Real-time communication for production systems
Cybersecurity	• The management of heightened security risks due to a high level of networking among intelligent machines, products, and systems
Big data and analytics	• The comprehensive evaluation of available data (from CRM, ERP, and SCM systems, for example, as well as from an MES and machines) • Support for optimized real-time decision making

Source: BCG analysis.
Note: SOP = standard operating procedure. CRM = customer relationship management. ERP = enterprise resource planning. SCM = supply chain management. MES = manufacturing execution system.

Figure 3. Nine technologies are reshaping production [16]

A study on the capabilities of IoT, Big Data and Analytics for CE has identified eight functionalities of these enabling technologies which are improving product design, attracting target customers, monitoring and tracking products, providing technical support, providing maintenance, optimising the product usage, upgrading of products, enhance renovation and end of life activities [18]. Rolls-Royce for example, has implemented specific IoT technologies to monitor the engine data received via satellites in real time, and automatically elaborates the collected data through appropriate analytics [19]. These data can be used in various kind of repair and maintenance approaches, which indirectly supports product life extension. Additive manufacturing (AM) has a huge potential in the circular economy as it is capable of providing parts and components which may not be available by the time a product reaches its end of life. Since AM can produce parts even with intricate features, it should be able to support remanufacturing and maintenance activities. Recently, the deployment of AM in parts restoration have been actively discussed by scholars [9],[20]. While this is still at its infancy, scholars have started to study the process capabilities of AM for parts restoration, development of new and compatible materials while designers are looking at the aspects of designing products for restoration using AM. Technologies such as RFID which have been used for locating and tracking purpose, will play a more significant role in CE as it is capable of collecting information about how products have been used in order to estimate the quality of returned products and facilitate the return flows into Product Life Cycle management [21]. A recent study on digitalisation in CE has proposed virtualisation as the key enabler in the adoption of a circular business model in order to support the design of modular and repairable products which can be updated [22].

5. Current challenges in Multiple Life Cycles

Despite the growing interest and acceptance of remanufacturing, upgrade and maintenance, these recovery strategies are still facing significant challenges such as poor design of products which do not support efficient recovery and maintenance, scarcity of cores, inconsistent supply of cores and consumers uncertainty on the quality and performance of remanufactured components. These challenges and how enabling technologies of IR4.0 can be deployed to mitigate them are outlined in table 1.

Table 1. Challenges in multiple life cycles and the support from enabling technologies

Multiple Life Cycle Challenges	Strategies	Enabling technologies and Platforms
Poor design of products affecting efficient remanufacturing, upgrades and maintenance.	Design for Remanufacturing and Multiple Life Cycles for ensuring durability, ease of disassembly and reassembly, ease of inspection and testing, modularity and upgrades, ease of maintenance.	Computer aided design, simulations and predictive tools, IoT for sharing of information and knowledge among OEMs, suppliers and independent remanufacturers.
Uncertainty in the quality of returned products.	Enhance networking among OEMs and suppliers. Design for durability and reliability, Improve maintenance and monitoring of parts conditions during their useful life	IoT, simulations and predictive tools, Augmented Reality tools, RFID
Poor perception on the quality and performance of remanufactured components	Increase the flow of information and knowledge to educate consumers irrespective of educational background; to promote the green culture	IoT for tracking and take-back Social Network; Eco-labelling
Unavailability of parts for replacement due to product obsolescence.	To ensure parts availability on-demand Automated repair and restoration of parts	Additive Manufacturing AI techniques for machine learning

6. Conclusion

In CE, products are developed with the need for restoration and regeneration in mind in order for them to undergo an extended life cycle or even multiple life cycles. To date, remanufacturing and upgrades have been identified as value added strategy in terms of resource efficiency. Despite its success in many industries such as the aerospace, automotive, electrical and electronics, remanufacturing is still facing obstacles which can be mitigated with the advent of enabling technologies of the IR4.0. The deployment these enabling technologies promises efficiency in the design and development and supply chain of products during their multiple life cycles. Despite the potential in these disruptive technologies, their implementation has to be harmonised with two other pillars of sustainable development, namely social and economy.

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