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# Design, management and control of demanufacturing and remanufacturing systems

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ABSTRACT

In the recent years, increasing attention has been posed towards enhancing the sustainability of manufacturing processes by reducing the consumption of resources and key materials, the energy consumption and the environmental footprint, while also increasing companies' competitiveness in global market contexts. De- and remanufacturing includes the set of technologies/systems, tools and knowledge-based methods to recover and reuse functions and materials from industrial waste and post-consumer products, under a Circular Economy perspective. This new paradigm can potentially support the sustainability challenges in strategic manufacturing sectors, such as aeronautics, automotive, electronics, consumer goods, and mechatronics. A new generation of smart de- and remanufacturing systems showing higher levels of automation, flexibility and adaptability to changing material mixtures and values is emerging and there is a need for systematizing the existing approaches to support their operations. Such innovative de- and remanufacturing system design, management and control approaches as well as advanced technological enablers have a key role to support the Circular Economy paradigm. This paper revises system level problems, methods and tools to support this paradigm and highlights the main challenges and opportunities towards a new generation of advanced de- and remanufacturing systems.

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## 1. Introduction, motivation and objectives

### *1.1. Context, opportunities and benefits of Circular Economy*

Circular Economy has been recently proposed as a new paradigm for sustainable development, showing potentials to generate new business opportunities in worldwide economies and to significantly increase resource efficiency in manufacturing [175].

The vision of the Circular Economy paradigm is to fundamentally change the current linear "take–make–dispose" economic approach, which is cause of massive waste flows. For example, in the fast-growing consumer goods sector alone, about 80% of the $3.2 trillion material value is lost irrecoverably each year worldwide [304]. In contrast, Circular Economy is an industrial system that is restorative and regenerative by intention and design [175]. It aims to keep products, components, and materials at their highest utility and value along their life-cycle. It replaces the product 'end-of-life' concept with restoration and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.

Recent studies show that a transition to Circular Economy may represent a new sustainable growth path as well as a business opportunity for the worldwide manufacturing industry [82]. In a world of close to 9 billion people expected by 2030 – including 3 billion new middle-class consumers – the challenges of expanding resource supply to meet future demand are unprecedented. Without a rethinking of how society uses materials in the linear economy, elements such as gold, silver, indium, iridium, tungsten and many others vital for industry could be depleted within the next 5–50 years [304]. A new industrial model that decouples revenues from material input, and production from resource consumption is needed for achieving a sustainable development path, both in early-industrialised countries and in emerging economies [243]. A sustainable transition to Circular Economy is expected to bring benefits in environmental, economic

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and social terms. In environmental terms, Circular Economy practices have potential to bring 80%–90% savings in raw materials and energy consumption with respect to the production of the same goods in the traditional linear model, strongly contributing to $CO_2$ emissions reductions and positively affecting the climate change. In economic terms, the major benefits of Circular Economy for manufacturers are brought by the reduction of material and energy costs coupled with the reduction of end-of-life materials disposal costs. This, in turn, translates into a general product price reduction of around 25%–30%, that can boost the availability of high quality affordable products, thus increasing companies' competitiveness in emerging markets. A recent study showed that by shifting toward a Circular Economy model the European economy could achieve annual benefits of €0.9 trillion by 2030, in addition to the €0.9 trillion that could potentially be brought by the ongoing European digital transformation of businesses [177]. In social terms, Circular Economy businesses are expected to bring new jobs by boosting an increased consumption of sustainable products driven by the lower prices.

Due to these features, Circular Economy is achieving increasing importance in the worldwide political and research agendas. The G7 Summit Declaration of June 2015 has launched the "Alliance on Resource Efficiency" to promote Circular Economy, Remanufacturing and Recycling as strategic actions for limiting the consumption of natural resources and reducing waste. At European level, the Commission launched in December 2015 the strategic initiative "Closing the loop — An EU action plan for the Circular Economy" [69]. In China, Circular Economy is seen as a new model for industrialisation and an integrated strategy to essentially reform the traditional patterns of economic growth and social development for contrasting the effects of the massive urbanisation and the environmental problems. Since 2006, Circular Economy initiatives are promoted in the Chinese "Five Year Plan" of development [305,253]. Similar initiatives have been initiated in US, Japan, and Australia.

However, a sustainable transition to Circular Economy businesses will need to be supported by fundamental innovations, driven by the manufacturing industry, at systemic level, encompassing product design, value-chain integration, business models, ultimately posing new challenges on the way demanufacturing and remanufacturing technologies and systems are conceived and implemented. Demanufacturing and remanufacturing, briefly indicated as *de- and remanufacturing*, are fundamental technical solutions for an efficient and systematic implementation of Circular Economy. More formally, *De- and remanufacturing includes the set of technologies and systems, tools and knowledge-based methods to systematically recover, reuse, and upgrade functions and materials from industrial waste and post-consumer products, to support a sustainable implementation of manufacturer–centric Circular Economy businesses.* While demanufacturing liberates target materials and components, remanufacturing restores or upgrades their functions.

This paper provides an overview and a framework of the industrial practices, scientific methodologies, and enabling technologies to profitably design, manage and control de- and remanufacturing systems. It also identifies key open research and practical issues that need to be addressed by the research community. The key questions that this paper addresses can be formulated as follows: "What are the main industrial barriers for a profitable implementation of Circular Economy businesses by manufacturers?" and "Which tools can support the development of the next-generation de- and remanufacturing systems?".

The paper is structured as follows. The next paragraphs present the key definitions and concepts concerning different options for implementing circular businesses and introduce a set of real cases that provide the industrial motivation to the problem. Section 2 proposes a new framework that highlights the role of the manufacturing industry in the implementation of Circular Economy solutions. Sections 3–5 revise, respectively, the state-of-the art methods and tools and the enabling technologies supporting the design, management and control of efficient de- and remanufacturing systems. Section 6 discusses socio-economic boundaries to Circular Economy. Finally, Section 7 describes promising future research topics in this area.

### 1.2. Definitions and key concepts

The Circular Economy concept cannot be traced back to one single date or author, but it finds its root in several schools of thought. The theory of "Regenerative Design" by Lyle introduced in the late 70s the idea of linking sustainable development to the concept of resource regeneration [174]. The economic basis for a transition to a non-linear industrial model was originally introduced by Stahel in Ref. [251] and further refined with the idea of "Cradle-to-Cradle" design [187]. It is an economic, industrial and social framework that seeks to create systems that are not only efficient but also essentially waste free. This model was applied to industrial design and manufacturing, social systems and urban environments. "Industrial Ecology" [75], i.e. the study of material and energy flows through industrial systems, also has links to the Circular Economy concept. Focusing on connections between operators within the 'industrial ecosystem', this approach aims at creating closed-loop processes in which waste serves as an input. As Circular Economy, also Industrial Ecology adopts a systemic point of view, designing production processes in accordance with local ecological constraints, while looking at their global impact from the outset. More recently, the "Blue Economy" movement originated by Pauli, collected practical cases where the resources are connected in cascading systems and the waste of one product becomes the input to create a new cash flow [209]. The modern concept of Circular Economy can be attributed to the MacArthur Foundation [176]. Four different mechanisms for value creation in Circular Economy were introduced that offer opportunities in comparison with linear usage. They are referred to as:

- *The power of inner circle*: the closer the product gets to direct reuse, i.e., the perpetuation of its original purpose, the larger the cost savings will be in terms of material, labour, energy, capital and the associated externalities.
- *The value of circling longer*: value created by keeping products, components, and materials in use longer within the Circular Economy. This can be achieved by enabling more cycles or by spending more time within a single cycle.
- *The power of cascaded use*: value created by using discarded materials from one value chain as by-products, replacing virgin material in another.
- *The power of pure circles*: uncontaminated material streams increase collection and redistribution efficiency while maintaining quality.

At technical levels, different business options for Circular Economy have been proposed to generate benefits by exploiting these value-creation mechanisms. For example, Jawahir in its definition of "Sustainable Manufacturing" proposes the so-called 6Rs model, where the traditional 3R model based on the Reduce, Reuse, Recycle practices is enriched with three additional actions namely Recover, Redesign, and Remanufacture [121,120]. In practice, the following Circular Economy options and the related business models are implemented in the industrial practice:

*Reuse:* a generic term covering all operations where a return product is put back into service, essentially in the same form, with or without repair or remediation [206].

*Repair*: the correction of specified faults in a product [206]. Repair refers to actions performed in order to return a product or component purely to a functioning condition after a failure has been detected, either in service or after discard [207].

*Remanufacturing for function restore*: it returns a used product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product. A remanufactured product fulfils a function similar to the original part. It is remanufactured using a standardised industrial process, in line with technical specifications [11].

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