Handbook of Sustainable Development through Green Engineering and Technology

Vikram Bali, Rajni Mohana, Ahmed A. Elngar, Sunil Kumar Chawla, Gurpreet Singh

Toward Circular Product Lifecycle Management through Industry 4.0 Technologies

Publication details
https://test.routledgehandbooks.com/doi/10.1201/9781003127819-5
Barbara Ocicka, Grayna Wieteska, Beata Wieteska-Rosiak
Published online on: 27 Sep 2022

5 Toward Circular Product Lifecycle Management through Industry 4.0 Technologies

Barbara Ocicka
Collegium of Business Administration, Department of Logistics, SGH Warsaw School of Economics, Warsaw, Poland

Grażyna Wieteska
Faculty of Management, Department of Logistics, University of Lodz, Lodz, Poland

Beata Wieteska-Rosiak
Faculty of Economics and Sociology, Department of Investment and Real Estate, University of Lodz, Lodz, Poland

CONTENTS

5.1 Introduction....70
5.2 Definitions and Principles of the Circular Economy....71
5.3 Circular Product Life Cycle....74
5.4 Integrating Industry 4.0 into a Circular Product Lifecycle....77
5.5 Case Studies on Implementing Industry 4.0 across Industries....78
5.5.1 The Construction Industry....78
5.5.1.1 Cloud Computing and Mobile Technologies....82
5.5.1.2 Building Information Modeling....83
5.5.1.3 Augmented Reality and Virtual Reality....83
5.5.1.4 Artificial Intelligence and Big Data....84
5.5.1.5 Drones....84
5.5.1.6 Blockchain....84
5.5.1.7 3D Printing....85
5.5.1.8 Internet of Things....85
5.5.1.9 Web Platforms....86
5.5.2 The Furniture Industry....86
5.5.2.1 Computer-Aided Design Programs and Generative Design AI-Based Algorithms....86

DOI: 10.1201/9781003127819-5

5.5.2.2 Blockchain 87
5.5.2.3 The Internet of Things and 3D Printing 87
5.5.2.4 Cloud Computing 88
5.5.3 The Cosmetics Industry 88
5.5.3.1 Advanced Co-creation Platforms 88
5.5.3.2 Blockchain 89
5.5.3.3 3D Printing 89
5.5.3.4 Cloud Computing 90
5.5.3.5 The Internet of Things, Augmented Reality, Artificial Intelligence, and Big Data Analytics 90
5.6 The Comparative Analysis of Industries 91
5.7 Conclusions and Implications 96
Acknowledgements 99
References 99

5.1 INTRODUCTION

The global challenge facing the modern world is to reduce human pressure on the environment while ensuring a high life quality and competitiveness of economies. The circular economy concept, which has recently become more popular, can be perceived as an approach that supports the achievement of sustainable development goals. The transition to a circular economy is an opportunity to create a low-carbon, resource-efficient, competitive economy and finally become climate-neutral (European Commission 2015; 2020). However, the dynamic growth of the world population, global consumption, and production are sources of the extremely high demand for natural resources, problems with waste growth, intensive greenhouse gas emissions, as well as the alarming climate change, which has resulted in the intensification of extreme climate phenomena (IPCC, 2013; Below and Wallemacq 2018).

Nowadays, when designing a product's lifecycle, one needs to consider the principles of the circular economy, which direct our attention toward the circular product lifecycle (European Environment Agency 2017). To successfully face the challenge of circular product lifecycle management, companies can exploit multiple diverse digital technologies in each of the stages, as well as throughout the entire lifecycle. The literature is filled with numerous theoretical studies dealing with this subject, although they approach the issue mostly from an overall perspective of the circular economy. It is broadly accepted that digital technologies support the transition toward a circular economy (Pagoropoulos et al. 2017; Antikainen et al. 2018; Okorie et al. 2018; Rosa et al. 2019). However, empirical studies that discuss the role of selected technologies are rare, and further studies on real company cases are desirable. Researchers underline the urgent need to conduct more empirical research on the adoption of technologies in case studies (Pagoropoulos et al. 2017).

This chapter explains how Industry 4.0 technologies can be integrated into the circular product life cycle within different industries. It starts with a presentation of the latest circular economy (CE) concept and its principles. This is the starting point for the next section, which introduces the definition and six phases of the circular product lifecycle (CPLC). The authors focus on Industry 4.0 technologies that they identified in the literature review and described regarding their functionality and role for CPLC development. Next comes an empirical study based on an analysis of multi-sector case studies that demonstrate the use of Industry 4.0 at different stages of product lifecycle management and their impact on the effective implementation of CE principles.

The reason behind the choice of sectors was twofold. On the one hand, the three selected industries (construction, furniture, and cosmetics) impact the quality of life of modern society by delivering products that meet the basic needs of consumers and households. On the other hand, however, they differ from each other regarding the complexity and value of these products. In the next section, a comparative analysis of the case studies is conducted based on CE principles and CPLC phases. It allows us to formulate the key conclusions and practical and theoretical implications outlined at the end of this chapter.

5.2 DEFINITIONS AND PRINCIPLES OF THE CIRCULAR ECONOMY

The global challenge of the modern world is to reduce human pressure on the natural environment while ensuring a high quality of life and competitiveness of economies. The current linear model is based on the principles of "take-make-dispose" (Ellen MacArthur Foundation 2013, p. 2; 2019a, p. 5), "take-make-consume-dispose" (European Environment Agency 2016, p. 5), or "take-make-consume and dispose" (European Commission 2014, p. 2); however, it has lost much of its pertinence. Shrinking natural resources, increasing amounts of waste, dynamic population growth, increasing consumption and production, the volatility of prices, and raw material supply risks, environmental pollution, high greenhouse gas emissions, as well as progressive climate change (IPCC, 2013; Deloitte 2016) have all shifted the attention toward sustainable development and a resource-efficient economy. The significant loss of resources, increasing resource extraction, and wastage that are inherent in the linear approach gave the impetus for the development of the circular economy model.

The assumption underpinning the CE concept is to keep resources in use. When a product reaches its "end-of-life" phase, the aim is to productively reuse materials and resources and create economic value in the economy, processes, or product life cycle. In this way, we achieve efficient resource management as well as waste minimization (European Commission 2014). The circular economy concept seeks to reduce the dependence of economic development on shrinking resources. At the same time, it works to achieve economic growth and create new jobs while minimizing waste and reducing economic pressure on the environment (Ellen MacArthur Foundation 2014; 2019a). This means that the transition of the economy to circularity brings with it environmental, economic, and social benefits. It is part of the design of sustainable development. The CE has become one of the tools that seek to support the shaping of sustainable development and enable the implementation of proposals in the document entitled Agenda for Sustainable Development 2030. The document was signed by 193 countries and is committed to achieving 17 global goals of sustainable development (United Nations 2015).

In the CE, raw materials, materials, and products must circulate in a closed loop, limiting waste generation and reducing pollution released to the environment. The CE is more than just a concept, it is a global strategy. As a framework that can be implemented in many sectors of the economy, it has also become an object of interest to the world of science and politics (Vermeulen et al. 2018).

One of the definitions presented in many publications is the following: The circular economy aims to maintain various products and raw materials as long as possible. The assumption is that they are useful and valuable in the economy (Ellen MacArthur Foundation 2015, p. 2). Numerous definitions presented in the literature help to identify the main features and specificity of the CE (Rizos et al. 2017, p. 6; Korhonen et al. 2018, p. 547).

The literature on the subject discusses numerous CE principles presented in a narrower or broader sense. The Ellen MacArthur Foundation points to three general principles: design out waste and pollution, keep products and materials in use, and regenerate natural systems (Ellen MacArthur Foundation 2019b). A wide variety of CE principles in the literature combine the "R-word." In the area of the circular economy, the literature most often refers to the 3R typology. The 3R principles (Reduce-Reuse-Recycle) are used the most often; an extended version, known as the 5R principles (Reduce-Reuse-Remanufacture-Recover-Recover), is, in turn, the most often suggested. These rules are related to the waste management hierarchy. There are also less frequently used classifications based on 4R, 6R and 7R, and even 10R (Reike et al. 2018; Campbell-Johnston et al. 2019). The most common rules are R0-R9. The literature contains two more principles: Re-mine and Rethink. The 10R principles are proposed in Table 5.1. The development of a circular economy model takes time. Achieving a lasting change in the economy does not happen overnight. It requires systemic thinking and the involvement of equal stakeholders: producers (new products, and business and market models), consumers (new consumer behavior and environmental awareness), public authorities (taking care of appropriate development policies, supporting the CE development, and supporting and financing circular initiatives), research and scientific institutions (technology development and innovation), and non-governmental organizations (promoting CE and circular activities). This means that it is necessary to involve public and private sector entities and resources.

The economy has evolved toward a digital economy. Research on the CE and technologies is developing rapidly, and the potential of digital technologies is increasingly more important for the development of the circular economy. The importance of technology is also emphasized by the European Commission in its development policy documents (European Commission 2020). Obviously, technology and the circular product lifecycle are positively interrelated. On the one hand, modern technologies support the design of a circular product lifecycle, and on the other hand, the development of a circular product lifecycle becomes an impulse for the creation of further digital innovations. The two stimulate each other for the benefit of the circular economy and sustainable development. Technologies offer opportunities for the CE principles implementation (Pagoropoulos et al. 2017; Sukhdev et al. 2018; Rosa et al. 2019).

TABLE 5.1
CE Principles

	Principle	Description
R0	Refuse	Refuse to use materials, resources, or products that are not indispensable, or replace them with other, more environment-friendly, digital ones. • consumers: refrain from buying; buy and use less; reject packaging waste. • producers/retailers/designers: refuse to use virgin and hazardous materials that pollute the environment; design processes to avoid waste.
R1	Rethink	Enhance the intensity of the use of a product by, e.g. making it available, re-using it. • consumers: share products – you do not have to own a product • producers/retailers/designers: sell products as services
R2	Reduce	Reduce demand for natural resources and materials, save resources, avoid waste in production, distribution, and consumption; generate less waste rather than think about how to dispose of it after it is generated, i.e. prevent rather than cure. • consumers: take good care of a product; use it carefully; use a product longer • producers/retailers/designers: design to minimize the demand for raw materials and resources in production
R3	Reuse	Reuse products, components, and resources in good technical condition, which are not waste and can fulfill their primary functions. • consumers: buy second-hand products, not or hardly used, which require minor repair or adaptation; use Internet auctions and offers of used products • producers/retailers/designers: sell or use unsold returns or products in damaged packaging; use recycled materials; re-use products, components, and resources in production; multiple uses of packaging (including for transport)
R4	Repair	Repair products, replace damaged parts, and continue using them in their primary functions; expand their useful life. • consumers: have a product repaired by a repair company or another consumer; repair it in a 'repair café' • producers/retailers/designers: send reclaimed products to service centers (own or third-party); treat repair as strategic; design easy to repair products; expand the useful life of products and avoid continuous repairs
R5	Refurbish	Renew your product and make it usable. • consumers: send a product to the service center • producers/retailers/designers: restore a product by replacing parts, modules, or components, leaving the structure of a complex product untouched; use technically advanced components (major repairs of buildings, machines).

(*Continued*)

TABLE 5.1 (Continued)
CE Principles

	Principle	Description
R6	Remanufacture	Use elements from a product that is no longer suitable for use. Use valuable parts in products that perform the same functions as the old one. • consumers: redirect the product to the service center • producers/retailers/designers: disassemble the structure of a multi-component product, replace or repair in an industrial process, parts to be recycled.
R7	Repurpose	Change the purpose for which a product or part of it is used. Give it value and new application goals. Use a discarded product, or part of a product, in a new product and in new applications.
R8	Recycle Materials	Recycle. The goal is to achieve the same or lower material characteristics. • consumers: segregate waste, buy products labeled as being made from recycled materials, • producers/retailers/designers: design products that can be made of recycled materials; design for recycling; process/remanufacture products and waste to recover materials; use recovered materials for primary or other purposes.
R9	Re-mine	Retrieve materials and components after the landfilling phase. • consumers: choose recovered/retrieved products • producers/retailers/designers: retrieve materials from landfills; reclaim valuable materials, products, and parts ("cannibalization")
R10	Recover (energy)	Recover energy from waste through incineration; use biomass.

Source: Vermeulen et al. 2018; Potting, et al. 2017; Reike et al. 2018; Morseletto 2020; European Investment Bank 2020; Ellen MacArthur Foundation 2017.

5.3 CIRCULAR PRODUCT LIFE CYCLE

Product lifecycle management (PLM) is an organized concept for designing, developing, and managing product and product-related information (Saaksvuori and Immonen 2008). It is implemented in various industries that design, manufacture, and support products (Stark 2016). The interest in PLM is especially driven by globalization, product complexity, shrinkage in product lifecycles, and environmental issues. Managing the product across the lifecycle connects various stakeholders who cooperate by jointly developing products and implementing lifecycle assessment (LCA) methodologies (Ameri and Dutta 2005).

The idea of product lifecycle has expanded significantly in recent decades, with examples including various lifecycle scenarios, approaches, and models (INCOSE UK 2017). As the circular economy concept directly relates to the product architecture, as well as designing, manufacturing, and distribution processes, we have decided to focus on engineering. The generally accepted definition of product lifecycle (PLC) in the ISO 14040 standard is the "consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal" (International Organization for Standardization 2006).

An engineering product lifecycle consists of several phases, which are usually based on a linear structure. The product lifecycle diagrams available in the literature on the subject differ in terms of the names of phases and the degree of detail, for example:

- Chen et al. (2009) depict the PLC using the following seven stages: product design, process development, product manufacturing, sales, the product in use, post-sales service, and retirement. In addition, each stage encompasses several activities.
- Terzi et al. (2010) illustrate a PLC in a four-level model. The main phases chronologically are: design and manufacturing (beginning of life), distribution, use and support (middle-of-life), and retirement (end-of-life). Each phase contains several elements, e.g. the design phase includes product design, process design, and plant design, while the support phase means repair and maintenance.
- Stark (2016) distinguishes only five phases: imagine, define, realize, support/use, retire/dispose.
- Ali et al. (2019), based on previous studies, indicate five PLC phases (design, manufacturing, usage, maintenance, end of life) and explain them through seven processes (needs recognition, design/development, production, distribution, usage, maintenance, disposal/recycling).

There is also clear evidence in the PLC descriptions that brings us to the topic of closing the loop, and it includes information and material flows that occur between the individual phases in the whole product lifecycle (Kiritsis 2011). The most thoroughly considered phase is the end of life, which aims to maintain the flows during or after a product is used. Scenarios such as reuse, recycling, remanufacturing, or disposal come up at this point, and implementing them connects the end-of-life phase with the previous phases (Ishii et al. 1994; Asiedu and Gu 1998; Kondoh et al. 2017). This kind of logic directly links with ensuring the circularity of raw materials as well as reducing waste. It is also a source of opportunities to continuously improve closed-loop flows. Namely, designers get feedback with detailed information from other PLC participants, and they can use it when reducing environmental impacts through designing improved products or processes (Young et al. 2007; Cao and Folan 2012; Lindkvist et al. 2017). There is a general agreement that the product design phase may determine all phases of its lifecycle, especially the end-of-life stage (Rose et al. 2002).

Discussions around the end-of-life phase led to other product-recovery scenarios being distinguished. Different reprocessing methods, depending on the product quality and the type of good, e.g. module and material, have been recognized (see, e.g. Parlikad et al. 2003; De Brito and Dekker 2004; Cao and Folan 2012). All these scenarios clearly overlap with the CE principles. Simultaneously, it is reflected in the publications on the circular economy, where there is a direct reference to the product lifecycle stages (Den Hollander et al. 2017; European Environment Agency 2017, pp. 7–11; Reike et al. 2018). This is not surprising since the CE is “the concept of closing material loops to preserve products, parts, and materials in the industrial system and extract their maximum utility” (Zink and Geyer 2017). Therefore, it is suggested to expand the circular product lifecycle term, which was presented in the literature (see, e.g. Kurilova-Palisaitiene et al. 2015), in the following definition:

> *“Circular product lifecycle (CPLC) is a product system consisting of several phases, from product design to product retirement, all of which are involved in the implementation of circular economy principles and are interlinked through closed loop material and information flows”*

The CPLC is presented as a circular graph, which consists of six PLC phases: design, raw material acquisition or generation, manufacturing, distribution, usage, and retirement (Figure 5.1). Both materials and information flow between these

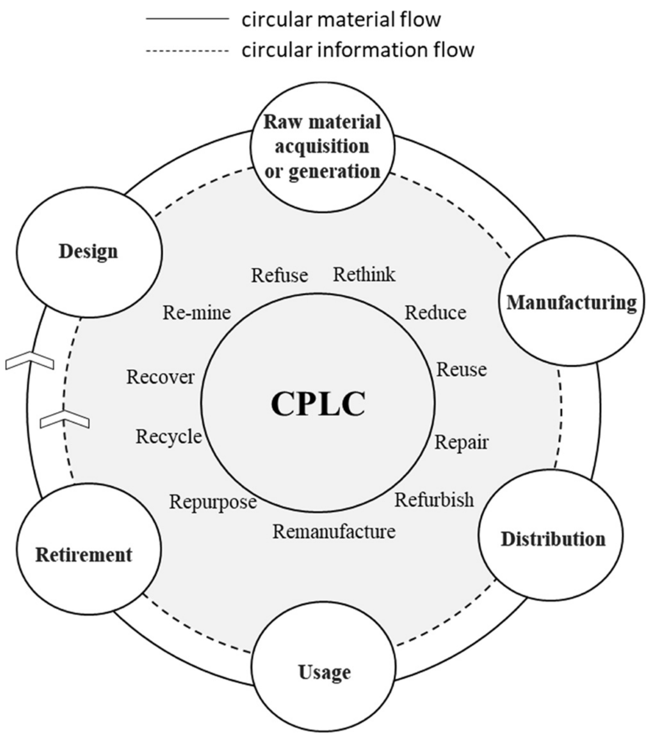

FIGURE 5.1 Circular product lifecycle.

Source: Own elaboration.

stages. The CPLC also includes all the 11 principles of the circular economy, which can be implemented at individual stages of the cycle and supported by various technologies.

The circular economy structure aims to retain the substances, resources, and final products for as long as possible and to eliminate waste at the same time. When a product's lifecycle is coming to an end, the challenge becomes maintaining resources in the loop and reprocessing them to create new value (European Commission 2014, p. 2). The traditional product lifecycle is an open-chain process rather than a closed-loop (Tóth Szita 2017). Growing production and consumption trigger the increase in demand for raw materials and waste generation, producing further environmental problems, which is why the design of the entire product lifecycle based on CE principles becomes crucial.

Since it is recommended that individual CE principles are simultaneously implemented by different product stakeholders (Potting et al. 2017; Reike et al. 2018; Vermeulen et al. 2018; European Investment Bank 2020), they generally concern more than one phase of the product lifecycle. All 11 principles lie at the center of design thinking and managing a product during the middle-of-life and end-of-life phases. To achieve the objectives of the CE, stakeholders within a sustainable product system should cooperate and exchange information and materials.

5.4 INTEGRATING INDUSTRY 4.0 INTO A CIRCULAR PRODUCT LIFECYCLE

The World Economic Forum, in cooperation with Accenture, highlights the significance of the 4th Industrial Revolution technologies (referred to as Industry 4.0 technologies) among the core pillars of the transformation toward a circular economy, including the digital, physical, and biological realms, and underlining their enormous impact on circularity (Lacy et al. 2020). Digitalization can boost the transformation from a linear to a circular product lifecycle, integrating the material and information flows regarding product characteristics, e.g. availability, location, or quality (Antikainen et al. 2018). Increasingly more advanced utilization of Industry 4.0 technologies creates novel ways to manage and optimize each phase of the CPLC, as well as the whole product-service system. These technologies can positively influence the development of CE capabilities and the circularity of resources within companies, increase efficiency in the use of resources and energy, improve maintainability, extend the lifecycle and value of the products, and enhance social and environmental performance (Dubey et al. 2019; Rajput and Singh 2019; Bag and Pretorius 2020; Piscitelli et al. 2020). Piscitelli et al. argued that the development of the CE is impossible without Industry 4.0 technologies, and it is impossible to develop a sustainable Industry 4.0 without the CE concept (Piscitelli et al. 2020). However, it should be noted that empirical research on the influence of Industry 4.0 technologies on implementing the CE is in its infancy (De Sousa Jabbour et al. 2018).

Note that, as yet, there is no consensus on the major types of Industry 4.0 technologies in the development of the CE. However, the following classifications can be mentioned as examples:

- Pagoropoulos et al. (2017) systemized digital technologies as follows: data collection, analysis and integration, RFID (Radio Frequency Identification), the Internet of Things (IoT), Relational Database Management Systems and database handling systems, PLM systems, machine learning, and Big Data analytics.
- Zhong et al. (2017) indicated cyber-physical systems, IoT, Big Data, and cloud manufacturing as key technologies.
- Kang et al. (2016) and De Sousa Jabbour et al. (2018) proposed an overview of the key Industry 4.0 technologies, including cyber-physical systems, manufacturing based on the cloud model, IoT, and additive manufacturing.
- According to the World Economic Forum's transformation map, the following technologies enable circularity: artificial intelligence (AI), robotics, aerospace, IoT, digital communication, mobile technologies, computing, advanced manufacturing, and production, as well as infrastructure (WEF 2020).

In the light of the literature review findings, the potential of the following Industry 4.0 technologies is presented in more detail: additive manufacturing, blockchain, cloud computing, data analytics, and the Internet of Things (Table 5.2).

Table 5.2 shows that Industry 4.0 can integrate information, improve decision-making, and enable the development and implementation of new strategies and processes in light of the CE concept. Their contribution to the phases of a product's lifecycle includes a range of 10R principles. Besides the fact that there are different ways to classify Industry 4.0 technologies and assess their significance for the development of the CE, academics and practitioners both emphasize the need for an interoperability approach to tap their full potential. At the same time, we should not ignore the various barriers that hinder the use of technologies that facilitate CPLC management. Rajput and Singh (2019) identified the following barriers: a lack of uniform standards and specifications, investment cost, the time required to implement and integrate technologies, challenges with compatibility and infrastructure standardization, difficulties in interfacing, networking, and upgrading technology.

5.5 CASE STUDIES ON IMPLEMENTING INDUSTRY 4.0 ACROSS INDUSTRIES

5.5.1 The Construction Industry

The construction sector has great potential for implementing the CE principles. The reasons are twofold: the intensive use of primary resources and the large amount of waste it generates. Globally, buildings generate around 40% of total waste and use 40% of mineral resources (Becqué et al. 2016, p. 21). The number of studies and literature reviews of the CE in the construction sector is increasing. The studies focus on the construction process, materials, products, recycled materials, the end-of-life phase, and construction and demolition waste management (Jin et al. 2019; Ginga et al. 2020). Circular solutions can be implemented at each stage of a building's lifecycle. Buildings should be designed to minimize the use of natural

TABLE 5.2
An Overview of Major Industry 4.0 Technologies within the Circular Product Lifecycle

Technology	Brief Description of Functionality	Product Lifecycle Phase	CE Principles Integrated
Additive manufacturing (AM), also called 3D printing	• relies on digital designing in CAD/CAE software, enabling hyper-personalization (even the economy of one) • reduces raw material consumption through additive (not subtractive) manufacturing • makes it possible to print components and products without tools, minimizing waste • makes it possible to manufacture new value-added products by printing from recycled materials (Kellens et al. 2017; Nascimento et al. 2019; Colorado et al. 2020)	Design Raw material acquisition or generation Manufacturing Distribution Retirement	R0 R2 R3 R6 R7 R8
Blockchain	• enables P2P controlled and transparent transactions to close the vulnerabilities of the Industrial Internet of Things • increases sustainability through monitoring and reporting social and environmental metrics (including a product's carbon footprint) as well as enhancing visibility and trust among entities engaged in the PLC • secures the control and replacement of consumables • provides real-time data synchronization and aggregation on a global scale • develops a smart contract-enabled multi-agent model to negotiate with or exchange know-how between process participants in the pursuit of a precise objective • eliminates the need for manual work and control, minimizing the probability of human error	End-to-end PLC	R0 R1 R2 R6 R8 R9

(Continued)

TABLE 5.2 (Continued)
An Overview of Major Industry 4.0 Technologies within the Circular Product Lifecycle

Technology	Brief Description of Functionality	Product Lifecycle Phase	CE Principles Integrated
	• provides unchanging shared data across external links and internal departments, supporting business process planning or resource sharing (Seebacher and Schüritz 2017; Cole et al. 2019; Esmaeilian et al. 2020; Leng et al. 2020)		
Cloud computing	• creates virtual and global space for sharing manufacturing resources and capabilities via the internet • centralizes distributed manufacturing resources and enables their sharing and high use on demand • is service based, meaning that business counterparties sell and buy services as well as reused and refurbished components or products • facilitates data management regarding types and amounts of waste or collection sites (Benlian et al. 2018; De Sousa Jabbour et al. 2018; Nascimento et al. 2019; Rajput and Singh 2019)	Raw material acquisition or generation Manufacturing Distribution Usage Retirement	R1 R2 R3 R5 R7 R8
Data analytics	• it is useful to collect data from different sources (including mobile technologies, social media, or electronic trading platforms) and then process and interpret the data into valuable information. As a result, it ensures information processing capability to optimize planning and procurement processes • ensures high capabilities to monitor production and consumption processes • provides findings based on raw and embedded data on multiple machines, tools, or products	Raw material acquisition or generation Manufacturing Usage Distribution Retirement	R0–R8

	• enables the implementation of new strategies and techniques in maintenance, reuse, and remanufacturing (Ge and Jackson 2014; Moreno and Charnley 2016; Srai et al. 2016; Pagoropoulos et al. 2017; Bag and Pretorius 2020; Kristoffersen et al. 2020)		
Internet of Things (IoT), also referred to as cyber-physical systems	• helps manage circular business models as dynamic and effective feedback control loops • provides current information about the activities of stakeholders throughout the entire PLC • increases efficiency in the use of tangible and intangible resources within PLM • improves data collection and sharing resource consumption and materials wastage, enhancing the effectiveness and precision of production systems • enables real-time product traceability, and improves the possibilities of collection at the end of lifecycle, refurbishment, remanufacturing, and recycling • supports predictive maintenance and service recovery while significantly reducing the probability of system failure (Manyika et al. 2015; Wortmann and Flüchter 2015; Reuter 2016; Antikainen et al. 2018; Bressanelli et al. 2018; Rajput and Singh 2019)	End-to-end PLC	R0–R10

Source: Authors' own elaboration.

resources, while the materials they are made of should be highly durable, environmentally friendly, and recyclable. Modular designs are preferred. At the construction site, the equipment should be used in an optimum way, and waste minimization needs to be ensured. For existing structures, revitalization is recommended. Buildings should be renovated and maintained regularly, using renewable energy sources and optimizing consumption. Resource sharing should be promoted by e.g. "sharing" office space after hours. In new investment projects, building materials should be recyclable or reusable (Deloitte 2016).

The use of technology in construction is recommended as it will ensure greater productivity, efficiency, and higher quality. Technologies are sources of the potential that can be used. They offer the opportunity to save costs and time, as well as reduce waste and pollutant emissions. Technologies that can be used in construction include robotics, drones, digital reality, IoT, AI, building information modelling (BIM), 3D printing, and blockchain (Deloitte 2019, p. 7). However, the intensity with which digital technologies are used in construction is still low, and the sector surely needs to advance in this area (Agarwal et al. 2016, p. 3). The literature identifies barriers to and drivers of the adoption of technology in construction. The barriers to using high technologies, such as AR or VR, include costs or the immaturity of the technologies, which are not developed enough to be comprehensively embraced by the sector. (Delgado et al. 2020a; 2020b). The same can be said about the awareness and use of BIM in construction (NBS 2020).

5.5.1.1 Cloud Computing and Mobile Technologies

Due to the role that the construction industry plays in the economy and its impact on the natural environment, the implementation of CE principles in the sector is extremely important. To maximize efficiency in the construction industry, it is important to ensure real-time access to the latest information from anywhere in the world since this facilitates cooperation and information exchange between employees and contractors. Cloud computing, in combination with mobile technologies, which are used by more and more employees, helps build a competitive advantage on the market.

These benefits have been recognized by Pico Volt LLC, which uses eSUB design software, which is based on mobile technologies and cloud computing. The company is engaged in consulting and electrical management services. The technology enables the proper planning of resources and materials when the company is working on several parallel projects, saving time and money. Ground Breakers Construction, thanks to eSUB, has control over reports, field work, and the flow of information between teams and office staff. All information is readily available in real time, and it is possible to view and log changes. As the company emphasizes, this solution has a clear advantage over paper document flows (eSUB 2020). Working in the cloud reduces errors and corrections, which, in turn, is reflected in project costs (Sage Construction and Real Estate 2015, p. 4). Cloud computing makes it possible to make and input changes from anywhere, not necessarily when in the office. It reduces the commuting burden on the environment and on employees who otherwise would have to travel to the office to deliver documents or make corrections in projects. The technology makes it possible to put the reduce principle in place by reducing design errors, demand for printing, and travel to the office.

5.5.1.2 Building Information Modeling

Building information modeling (BIM) is an increasingly widely known technology applied at the design stage because it can generate a digital model of a building. It supports cloud computing, and it is also designed to facilitate collaboration between different industries involved in the construction process by making the 3D model available to them. BIM is used throughout a building's entire lifecycle to ensure better cooperation in design, construction, and at the facility management stage.

A high-profile example of BIM in action was in the construction of the Shanghai Tower. By applying BIM in this investment project, the investor managed to reduce construction waste, errors made at different stages, and the resulting necessary technical corrections. The tool allows the user to determine the demand for resources necessary for the project, and in the Shanghai Tower construction, consumption of materials decreased by 32%. The software enables optimal management and maintenance of the building through appropriate renovation, building maintenance, and failure identification. The building uses renewable energy sources and solutions required by the LEED certificate (Autodesk 2020).

The use of BIM across the industry will hopefully grow with the development of sustainable construction and certification. BIM can also be used in the retirement stage. The technology makes it possible to optimize demand for materials, reduce their use in construction, minimize waste, and make decisions at the management stage about appropriate repairs (to extend the lifespan of buildings). It can also be used to recover construction and demolition waste (HISER project 2020). Thus, this technology contributes to the implementation of CE principles: Refuse, Reduce, Reuse, Recycling.

5.5.1.3 Augmented Reality and Virtual Reality

Design offices compete in the market to win potential clients' attention. AR and VR technologies are beneficial solutions helpful for designers. They make it possible to better adjust a project to the customer's needs and requirements. They are used by companies such as Design Group Latinoamerica, Design Hause Architecture, GASHU Arquitectos, and Darf Design. The technology lets customers choose optimal solutions, and as a result, minimize the number of errors and changes in the design. Used at the design stage, technology reduces the number of errors at the construction stage. It saves time and money, as well as resources and materials, including paper (Albornoz 2018; Darf Design 2020; Design Group Latinamerica 2020; GASHU Arquitectos 2020).

The potential of the technology is also seen at the construction stage, where it reduces possible clashes between different solutions occurring on the construction site. Smart helmets and glasses are examples of such technologies, while special applications can also be developed. The technology has several uses: it allows the user to make better decisions in the construction process, it can convert a 2D image into a 3D one, virtual measurements can be made, and the results can be compared with the design in real time. The technologies make it possible to get a 3D image of the constructed elements and installations, and they can help reduce the number of errors on the construction site through quick reactions and corrections made by the contractor. As a result, less waste is generated at the construction site, and demand for new materials is reduced (Suoza 2019). Under the CE, it is possible to implement the rules of Refuse and Reduce.

5.5.1.4 Artificial Intelligence and Big Data

Time-cost optimization is a major challenge facing the construction sector, which is why the manufacturing and construction stages require proper preparation. This was noticed by the Hawaiian Dredging Construction Company, Toda Corporation, Kajima Corporation, Build Group, Multiplex, Rio Tinto, Takenaka Corporation, and DPR Construction. Using ALICE technologies – a construction simulation and optimization platform – they focused on artificial intelligence and big data technologies. The tool lowers investment costs and reduces the time needed to complete the project. It helps develop the best investment scenario by analyzing several solutions and selecting the best options. Additionally, it optimizes investment projects when it comes to necessary resources (the number of employees), the location of machines on the construction site, the availability of materials and contractors, and planning the sequence of activities. As a result, it saves materials and resources, including fuel (ALICE Technologies 2020). Savings are subject to circular rules such as Refuse (abandoning resource-intensive solutions) and Reduce (reducing the demand for materials and raw materials).

5.5.1.5 Drones

The potential of drones is recognized in the design and manufacturing stages. An example of using this technology was its implementation in the T2 highway project in Estonia. Drones make it possible to take accurate geodetic measurements and accurately determine the demand for gravel and sand for road construction. The Estonian government was able to compare estimates obtained from drones with those from the contractor. The technology saves time and money (Wingtra 2020), allowing the user to save resources and put the Reduce principle into practice.

5.5.1.6 Blockchain

Designers and contractors are not the only stakeholders from the construction industry who should be involved in the CE. From the CE perspective, the materials from which a facility is built are crucial. How they are produced should fit into the principle of sustainable development and take place in a closed loop, and blockchain technology seems to be the best choice. It creates an opportunity to increase trust between companies and standardize and trace the origin of materials.

The Mining and Metals Blockchain Initiative is a consortium that has realized what this technology has to offer. Together with the World Economic Forum, in 2019, the consortium established seven mining and metallurgical companies. The goal was to design and implement blockchain solutions that would support the responsible extraction of raw materials (World Economic Forum 2019). One of the members of the consortium is Tata Steel, a steel manufacturer that operates in line with the CE principles (Hodgson and Brooks 2018). They used blockchain in a pilot project to determine the entire lifecycle of a steel beam from production to its reuse or recycling. The steel beam is tracked with a unique ID registered within the blockchain system. The material passport the company proposed allows the user to track the product (including transport) and use it in the BIM model. All information on steel beams is available to interested parties (Institution of Civil Engineers 2018, p. 31). Blockchain enables material identification and recovery, and it makes it possible to Reuse, Remanufacture, or Recycle.

5.5.1.7 3D Printing

3D printing technology has also demonstrated its high potential in the construction sector. It helps to quickly complete a building and save funds and resources. The largest building in the world made using 3D printing technology was completed in 2019 in Dubai. The building is 9.5 m tall, and its rentable area is 640 m^2. The building was constructed on-site with one printer using the local material supplier (Cheniuntai 2019). In 2018, the GAIA house in Italy was built in 3D. This is a passive building, built on-site in a few weeks from waste rice husks, raw earth, straw, and lime, all of which were sourced locally (Chiusoli 2018).

The technology helps to reduce possible errors on the construction site, and it reduces the demand for materials and the amount of waste. It can also be used to build permanent structures. The demand for equipment, machinery, and fuel decreases as only one printer is used, while the materials used for printing can be environmentally friendly and recyclable. 3D printing technology contributes to the implementation of the principles of Refuse, Reduce, Repurpose.

5.5.1.8 Internet of Things

The Internet of Things technology is used in smart buildings and is associated with using a Building Management System (BMS). As numerous sensors are installed in the buildings to help manage the facility, a BMS can control lighting, the HVAC system (heating, ventilation, air conditioning), and security systems. Additionally, it optimizes building conditions and reduces the demand for resources. A BMS identifies failures in installations and user preferences, seeks to meet them, and adjust ambient conditions to the user's needs. Examples of smart buildings are Google's New London HQ (Urie 2019, p. 7) or Cisco in Bedfont Lakes (Johnson Controls 2015).

The IoT enables the delivery of materials and components just in time using RFID (radio frequency identification). It allows the right number of orders for a given need, not more. The IoT and GPS data enable the tracking of machines and tools, improving their efficiency, extending their service life, and saving fuel. The IoT also makes it possible to track employees, which improves their efficiency and safety (Urie 2019).

RFID is a technology that supports construction companies. It is used to monitor materials, equipment, and workers on the construction site, which helps to better organize work and deliveries. The list of companies using this technology includes Kiewit, Twin Contractors, and HITT Contractor (Constructech 2012). The IoT offers the potential for the principles of Refuse, Reuse, Reduce, and Rethink. It takes care of machines, extends their useful life, and improves efficiency, while also saving resources and reducing waste.

5.5.1.9 Web Platforms

Excess materials-exchange platforms are becoming increasingly popular in the construction industry because they allow resources and building materials to be reused in new investment projects. For example, in 2018, VLA Architecture used the Opalis platform on a project to renovate an architectural office in Brussels (Belgium). Eighty percent of the materials that were used in the renovation project were recovered (Opalis 2020). Similarly, AgwA, another Belgian architectural firm, changed the function of an office building into a school, and the materials recovered from the office building were used in the school's design. The exchange of materials is a step forward in advancing the CE in construction, reducing demand for raw materials and giving materials a chance for a second life (Reduce, Reuse, and Repurpose).

5.5.2 The Furniture Industry

The furniture sector faces many barriers that significantly hinder its transition toward the circular economy. These barriers include low-quality materials and poor design, which restrict the potential for a successful second life of products. They also have poor product design, low specification standards of the recycled content and design for the circular economy principles, poor consumer information, the availability of spare parts that could prolong and extend a product's lifespan, the limited, high cost of repair and refurbishment, low demand for second-hand furniture and recycled materials, and underinvestment in collection and reverse logistics and the reuse, repair and remanufacturing infrastructure (Forrest et al. 2017, pp. 15–16). These challenges confirm the validity of the research question: Is Industry 4.0 a driver of successful change towards circular furniture lifecycle management? In addressing this question, researchers focus on the innovative practices implemented by various furniture companies around the world.

5.5.2.1 Computer-Aided Design Programs and Generative Design AI-Based Algorithms

A breakthrough innovation for the furniture industry is the use of computer-aided design (CAD) programs that enable 3D design, the introduction of an infinite number of corrections, and the use of a wide database of digital components. In recent times, computer-aided design has been enriched with the possibilities offered by AI via generative design. This concept uses AI algorithms to create various design options, simultaneously considering real-life manufacturing limitations and specific product requirements (Love that Design 2020). Generative design and 3D printing open up the realm of new design opportunities that would be impossible using the human mind alone.

Herman Miller's COSM chair is given as an example because its design involved 3D technology. It is praised for its excellent ergonomic performance, and its suspension is tailored individually to each user's spine, providing total spinal support.

The company offers 3D models and planning tools that customers can use in space-planning applications, such as Revit, and 2D and 3D AutoCAD files (Herman Miller 2020). This practice helps to plan real needs, reduces demand, and prevents resource waste, reflecting the CE principle of Reduction.

5.5.2.2 Blockchain

The use of Industry 4.0 technologies in the phase of raw material acquisition or generation is the first stage of growth in the furniture industry, as managers increasingly pay attention to the applicability of blockchain technology, especially in global sourcing. One company that has declared an interest in implementing this technology is Bassett Furniture & Home Décor (Slaughter 2018). It relies on third parties for much of its global sourcing, especially in Asia and South America; thus, blockchain technology could significantly increase the security of furniture supply chains because it ensures product tracking through all phases and helps fulfill compliance requirements. The functionality of this technology allows companies to enhance the quality of their products and reduce the waste of resources.

5.5.2.3 The Internet of Things and 3D Printing

Furniture plants are increasingly more technologically advanced, and German furniture maker Goldbach-Kirchner is developing the concept of networked production. Electronic manufacturing services (EMS) systems transfer data to other systems, enabling the automatic organization of manufacturing processes. Thanks to automation, robotics, and machine-to-machine (M2M) communication in the IoT environment, many benefits are achieved, such as the optimization of resource consumption and equipment utilization, as well as preventive maintenance.

Another technology that is changing production systems in the furniture industry is additive manufacturing. The largest furniture manufacturer in the world, Ashley Furniture, serves as an example. The company benefits from the advantages of 3D printing, like increases in productivity and quality, as well as a reduction in waste. This technology ensures there are over 700 parts in service in its factories (Colyer 2019). 3D-printed parts are used to simplify adjustments between product changeovers, and they ensure quick replacement. In summary, using both the IoT and 3D printing integrates such CE principles as Refuse, Reduce, and Remanufacture.

Furniture companies individualize products and strive to ensure the highest possible levels of customer experience and furniture comfort by implementing the IoT. An example is the Navigo Smart chair offered by Polish company Nowy Styl. The chair is equipped with a microcomputer and ultra-low energy technology that connects it with a computer or a smartphone (Nowy Styl 2020). The sensors monitor the chair's adjustment and the user's behavior, and it measures the physical conditions of a workstation (e.g. temperature, humidity, and air pressure). The data are analyzed and used to determine whether the user is sitting in an ergonomic position and working in optimal conditions. This combination of product and service is in line with the CE principles of Rethink and Reduce.

Smart solutions increase the intensity with which the same piece of furniture can be used, extending its useful lifetime in the most suitable environmental conditions. Some furniture companies concentrate their efforts on integrating the CE principles in the retirement phase. An example of good practice is the *Circular Product Design Guide of IKEA*, which relates to principles such as Reuse, Refurbish, Remanufacture, and Recycle. One of the technologies used to extend the product lifecycle is the 3D printing of spare parts for furniture (Iles 2018).

5.5.2.4 Cloud Computing

Furniture companies such as Ahrend, Fernish, Gispen, Ikea, and Vepa, take advantage of the possibility to efficiently extend product lifecycles by offering a new service in distribution – Furniture-as-a-Service (FaaS) via cloud-computing applications. This distribution model is based on furniture leasing, for which customers pay a periodic fee and can return the furniture when it is no longer needed. The office furniture manufacturer Ahrend is one of the pioneers in this business model. The company reports numerous benefits of the FaaS model within the PLC, such as the reduced need for natural resources and energy related to material extraction and processing, lower carbon emissions and environmental impacts, closer relationships with customers, higher potential for profits, the possibility of recovering components and materials that can be used to make new furniture, reduced office set-up costs, and higher flexibility for customers (Ellen MacArthur Foundation 2020). The FaaS distribution model influences other phases of the PLC, such as raw material acquisition, generation, and use. Finally, this technology contributes to the implementation of the following CE principles: Rethink, Reuse, Repair, Refurbish, Remanufacture, and Recycle.

5.5.3 The Cosmetics Industry

The global cosmetics market has grown rapidly in recent decades. It is especially driven by rising consumer income and changing lifestyles (Łopaciuk and Łoboda 2013), with clients increasingly looking for natural ingredients, green products, new packaging styles, and advanced beauty treatments (Rajput 2019). This forces companies to develop innovative products using the latest technologies and exerting less impact on the environment. Thus, strong players, in particular, increasingly start to focus on the principles of the circular economy (Fortunati et al. 2020). The literature contains publications that combine the latest research into innovative cosmetics ingredients and cosmetics packaging development with circular economy models (Cinelli et al. 2019; Fidelis et al. 2019; Lourenço-Lopes et al. 2020). There is a general recommendation and interest in both implementing LCA and tracking issues concerning the environmental, carbon, and water footprints in the cosmetics industry (Cosmeticseurope 2018, p. 4). Cosmetics companies also decide to deploy digital marketing and utilize information systems to enhance their market share (Kumar 2005). The latest reports show that Industry 4.0 technologies is an important determinant of the development and implementation of product and process innovations in the beauty sector.

5.5.3.1 Advanced Co-creation Platforms

Open innovations are becoming an important developing factor in the cosmetics industry. Procter & Gamble Co. (P&G) has launched a “Connect + Develop” co-creation platform to connect the company with companies and individuals who have innovative solutions for design, packaging, technologies, research, and engineering. The external collaborations allow P&G to improve its internal processes and design new products to meet the real needs of today's consumers, whose awareness of environmental problems is growing. They are involved in around 50% of P&G's designs (Procter & Gamble 2020). The result of the global company's open innovation strategy was about 2,000 formal contracts with partners from different countries (Ozkan 2015). P&G is actively involved in implementing the 3R (Reduce, Reuse, Recycle) principles through the PLC. The company plans to have 100% recyclable or reusable packaging by 2030, and it is also devoted to reducing energy use, greenhouse gas emissions, and truck transportation kilometers (Procter & Gamble 2019, pp. 5, 12). One of the last projects based on the company's extensive cooperation with NGOs and volunteers was the introduction of the recyclable shampoo bottle made from beach plastic (Head & Shoulders 2020).

5.5.3.2 Blockchain

Consumers increasingly care about reliable information concerning the origin and composition of cosmetics. However, the cosmetics industry is still not strictly regulated; thus, more and more companies have decided to implement blockchain in their supply chains. In particular, this technology ensures ingredient transparency, providing reliable information on the brand's story and products (CB Insights 2019, pp. 50–51). For example, Cult Beauty is a pioneer in bringing verified information into its online retail ecosystem. Thanks to Proof Points, the Provenance blockchain platform, a network of cooperating brands share information both on the supply chain links (from suppliers of raw materials to points of sale) and confirmed product characteristics (e.g. cruelty-free, vegan). This way, the company deals with social and environmental impacts across the whole cosmetics product lifecycle by being compatible with CE principles such as Refuse or Reuse.

5.5.3.3 3D Printing

In the beauty industry, many companies have already become interested in using 3D printing at different stages of the cosmetic lifecycle. For example, L'Oréal has implemented it for the fast prototyping of packaging, as well as for the rapid creation of spare parts or format parts in factories (L'Oréal 2020a). Thus, thanks to additive manufacturing, the use of raw materials and the generation of waste are reduced. L'Oréal also promotes the CE by preserving natural resources (e.g. water reuse in 'dry factories') and focusing on making 100% of packaging compostable, recyclable, reusable, or refillable by 2025 (L'Oréal 2018, pp. 6, 13).

Consumers can now also take advantage of the 3D makeup printer offered by New York-based beauty company Mink. This device transforms any image into wearable makeup (Mink 2020). Another example is Lancôme, which has introduced an innovative color-blending technology for its clients. At the sales point, the client's skin is scanned to determine its tone, and then, after some smart calculations are carried out, a unique customized foundation is printed (Lancôme 2020). This allows for personalized shopping, with each client receiving an individual complexion ID and the name on the foundation bottle for easy refill. Consumers not only take less time to choose the right product but, above all, they avoid buying an inadequate cosmetic product that would quickly cause dissatisfaction and then be left unused and turn into waste. As a result, waste is reduced, and the glass packaging can be reused.

5.5.3.4 Cloud Computing

Polish cosmetics manufacturer Farmona decided to change its IT model to ensure flexibility in responding to the current needs of online customers. The cosmetics industry is characterized by relatively high seasonality, e.g. in the holiday months, there is a significant increase in the number of page hits and transitions between the product websites, the company website, and the online store. Clients also stay longer on individual subpages than in other months (Polcom 2020).

Using the computing power provided by the Polcom Data Center guarantees that the servers are constantly monitored and covered by a comprehensive backup system. Cloud computing also allows for the maximum use of e-commerce sales channels and ensures production volumes appropriate for the size of the real demand. Thus, excess production is avoided, reducing inventories and the waste of products that have exceeded their shelf life.

5.5.3.5 The Internet of Things, Augmented Reality, Artificial Intelligence, and Big Data Analytics

In the beauty industry, the Internet of Things is also exploited at the distribution and use stage. Kérastase, which specializes in hair care products, offers a smart hairbrush, the Kérastase Hair Coach, which uses technology developed by Withings, the French consumer electronics company. The product has several built-in sensors, a vibrator, and a microphone. It connects to a dedicated smartphone app, which collects data (e.g. the number of brush strokes), provides tips based on hair type and brushing method, and suggests other products from the Kérastase line (Allure 2017).

HiMirror, offered by Taiwan's New Kinpo Group, is another popular smart product in the beauty industry. It is a technologically advanced device that supports the user during make-up and skin care routines. It analyzes skin through photos and stores measurement data allowing users to track their skincare results over time. An additional function is that it recommends cosmetics or reminds the user when products are about to expire. Apart from being connected to the internet, HiMirror uses AI technology. It scans the face and helps to explore and select the best make-up products by showing the results of their application virtually (HiMirror 2020).

The Makeup Genius smartphone app, which incorporates thousands of L'Oreal products and over a hundred unique facial expressions, lets users test and shop for color cosmetics online (L'Oréal 2020b). A similar beauty maker tool for consumers was launched by Coty. This beauty company also developed a smart Magic Mirror in collaboration with Holition (a creative innovation studio) and PERCH (an in-store retail marketing platform) (Coty 2020). The smart products are used not only to choose color cosmetics, but also to advise on the most appropriate skin care cosmetics.

LuluLab is a spin-off company created under the Samsung C-Lab program. It has launched LUMINI, an innovative device that digitalizes facial skin using AI and a fast algorithm for face scanning. It then recommends the best cosmetics (e.g. creams) following big data analytics (LuluLab 2020).

Selecting cosmetics is still one of the biggest problems facing consumers today. Not only is it time-consuming, but most of all, it often leads to unnecessary purchases, which then become unnecessary waste in the consumer's home. The examples of phone apps and digital mirrors discussed above not only solve the consumer's decision-making problems, but they also reduce the use of raw materials and promote waste minimization in the cosmetics industry.

5.6 THE COMPARATIVE ANALYSIS OF INDUSTRIES

Table 5.3 presents a comparative analysis of case studies from the selected industries. It identifies the similarities and differences in the implementation of technologies at different stages of the PLC, and it is an opening for a discussion on the potential of technologies in supporting the implementation of particular principles of the circular economy.

In this study, the CPLC consists of several phases (Figure 5.1) that integrate various CE principles (Table 5.1). The case study analysis shows that for each stage of a product's lifecycle, regardless of the type of industry, one or more Industry 4.0 technologies can be recognized. Companies are interested in implementing advanced approaches for different products with varying degrees of complexity, demand uncertainty, or lifecycle length. The comparative analysis shows that the use of individual technologies in the construction industry affects a much greater number of PLC phases compared to other industries. Depending on the industry, technologies also dominate in different phases. In the cosmetics and furniture industries, the distribution and use phases are characterized by greater exploitation of technologies, suggesting that the companies are focused mainly on the consumer market. In the construction industry, the technologies are implemented in the design, manufacturing, and use phases. Generally, it can be noted that the potential of Industry 4.0 is not fully exploited, especially at the raw material acquisition or generation phase. Furthermore, the more complex the architecture, the more technically advanced the product, and the higher the unit price, the more companies are likely to implement Industry 4.0, especially at the first phases of the PLC.

Technologies clearly integrate the adjacent phases of the PLC. Thus, the same technology usually determines more than one phase. This should encourage participants in the lifecycle of individual products to foster collaboration and joint investment in technology.

The key closing phase in the engineering product lifecycle is retirement. Unfortunately, while it is very important for closing the product lifecycle, it is not found in every industry. In the case of cosmetics, after the product has been used, only the packaging remains for recovery scenarios. In the furniture industry, packaging has mainly a logistical function, and at the retirement stage, there are products that either no longer satisfy the customer or require replacing for technical and safety reasons. The situation is completely different for long-lasting and complex construction structures. Another aspect is that, in the case of fast-moving consumer goods, the product moves faster to the retirement stage. Therefore, in this

TABLE 5.3
Industry-Specific Analysis of Industry 4.0 Technologies that Support the Implementation of CE Principles

Case	Company Name	Implemented Technology	Phase of the PLC that the Technology Relates to	The CE Principle that is Implemented through the Technology or Supported by the Implementation of the Technology
Construction	Pico Volt LLC Ground Breakers Construction	Cloud computing Mobile technologies	Design, Manufacturing	Reduce
	Gensler (project: Shanghai Tower)	Building information modeling (3D-7D)	Design, Manufacturing, Use, Retirement	Refuse Reduce Reuse Recycle
	Design Group Latinoamerica, Designhaaus, Gashu Arquitectos, Darf Design, construction companies	Augmented Reality, Virtual Reality	Design, Manufacturing	Refuse Reduce
	Hawaiian Dredging Construction Company, Build Group, Toda Corporation, Kajima Corporation, Multiplex, Rio Tinto, Takenaka	Artificial intelligence, Big Data	Design, Manufacturing	Refuse Reduce

	Corporation, DPR Construction, ALICE Technologies 2020			
	Hades Geodeesia	Drones	Design, Manufacturing	Reduce
	Tata Steel, The Mining and Metals Blockchain Initiative	Blockchain	Raw material acquisition or generation, Manufacturing	Reuse Remanufacture Recycle
	Apis Cor, WASP in association with Rice House	3D printing	Manufacturing, Retirement	Refuse Reduce Repurpose
	Heatherwick Studio and Bjarke Ingels Group (project: Google's New London HQ), Cisco, Johnson Control (project: building in Bedfont Lakes), Kiewit, Twin Contractors, HITT Contractor	Internet of Things (smart building, Building Management Systems) RFID	Use, Distribution, Manufacturing	Refuse Reuse Reduce Rethink
	VLA Architecture, AgwA	Web platform	Retirement	Reduce Reuse Repurpose
Furniture	Herman Miller	Computer-Aided Design programs and generative design AI-based algorithms	Design	Reduce
	Basset Furniture & Home Décor	Blockchain	Raw material acquisition or generation	Reduce

(Continued)

TABLE 5.3 (Continued)
Industry-Specific Analysis of Industry 4.0 Technologies that Support the Implementation of CE Principles

Case	Company Name	Implemented Technology	Phase of the PLC that the Technology Relates to	The CE Principle that is Implemented through the Technology or Supported by the Implementation of the Technology
	Goldbach-Kirchner, Ashley Furniture	Internet of Things, 3D printing	Manufacturing	Refuse Reduce Remanufacture
	Ahrend	Cloud computing	Distribution Use	Rethink Reuse Repair Refurbish Remanufacture Recycle
	Nowy Styl	Internet of Things	Use	Rethink Reduce
	IKEA	3D printing	Retirement	Refurbish
Cosmetics industry	Procter & Gamble	Advanced co-creation platform	Design	Reduce Reuse Recycle
	L'Oréal, Mink	3D printing	Design, Manufacturing	Refuse Reduce Reuse Recycle Repurpose

Cult Beauty	Blockchain	Raw material acquisition or generation, Manufacturing, Distribution	Refuse Reduce
Lancôme	3D printing	Manufacturing, Retirement	Reduce Reuse
Farmona	Cloud computing	Manufacturing, Distribution	Reduce
LuluLab	Artificial intelligence, big data analytics, Internet of Things	Distribution, Use	Refuse Reduce
Kérastase, New Kinpo Group, Coty	Internet of Things, augmented reality, artificial intelligence	Distribution, Use, Retirement	Refuse Reduce

Source: Authors' own elaboration.

industry, it is particularly important to develop efficient ways to collect and reprocess waste.

Product price is important to the consumer. In each industry, the end-product has a different price and is produced on a different scale. In construction, each investment implies extremely high costs, while furniture and cosmetics have a different economic dimension. The profitability of using the technology will depend on economies of scale at each stage of the product lifecycle. In the age of sustainable development and dwindling resources that are increasingly more expensive, every technology and every industry should strengthen its resilience and competitiveness to be able to survive. This is true of all industries because they all face a common problem of environmental degradation and fewer available resources. The solution lies in adopting the circular economy principles, and technologies that are now becoming the key to building enterprises' and economies' competitive advantage are helpful in this.

The specifics of the industries are reflected in the use of technology and its significance for the implementation of CE principles in a product's lifecycle. Complying with these principles or achieving sustainable benefits are rarely mentioned among the main reasons behind Industry 4.0. The key factors that lead to their implementation are economic, and include costs, flexibility, quality, and customer service. This is a surprising observation because, as the analysis of the case studies shows, fulfilling each CE principle can be supported by Industry 4.0 technologies, which significantly determine whether the sustainable goals are achieved. However, only a few companies (for example, IKEA) have so far developed strategies and policies that respond to the needs and requirements of managing the circular product lifecycle.

It should be clearly highlighted that industries have considerable potential – although not fully tapped – to implement all CE principles through the use of technology. The comparative analysis of industries demonstrated that Industry 4.0 technologies are at different levels of application maturity, depending on the product, stage of its lifecycle, and industry. The most common principles implemented by technologies are 3R, in particular, Reuse, Reduce, Recycle, with the Reduce principle being applied most often. As indicated in the literature on the subject, these principles are most popular in works on the CE. They are associated with directly reducing the demand for resources, raw materials, and materials, as well as reducing waste.

Companies integrate different Industry 4.0 technologies and benefit from their interoperability, and the synergy of using different technologies allows them to achieve greater sustainable effects. The same technologies lead to similar results, regardless of the industry. This empirical observation allows us to recognize significant opportunities for benchmarking and transferring technology projects not only between companies from the same industry but also from different industries.

5.7 CONCLUSIONS AND IMPLICATIONS

The circular economy is defined as a term, an economic strategy, a strategy, an alternative to the linear economy, an industrial system (restorative and regenerative), and an approach to resources. The flows of materials and resources in production and consumption are being arranged in a new, closed cycle – the opposite of the linear approach. Circularity is achieved through resource efficiency and effectively designing business models, and a product's lifecycle. Resources, materials, and products are maintained in the economy for as long as possible by giving them a circular flow. The aim is to use them to the maximum in the economy. Resources are recovered and pumped into the next circulation, extending their economic value. Waste is considered even at the design stage, as the goal is to minimize waste and the wastage of resources. At the end of the lifecycle, waste can become a resource with new value in the economy. A sustainable and circular economy is based on the use of renewable energy sources. The CE ensures economic growth (while reducing dependence on primary resources), the competitiveness of economies, new jobs, enterprises with new specializations, and it brings forward the development of innovation and technology. The underlying assumptions are the protection of the environment and the improvement of life quality of the present and future generations. Many definitions of CE indicate these features (Rizos et al. 2017, p. 6; Korhonen et al. 2018, p. 547).

The implementation of CE principles in the economy is already taking place. The significant role of technologies is noted in this process, although their implementation in the presented industries is still low on a global scale. This is certainly related to the continuous development, gradual implementation, and low availability of technologies. When introducing Industry 4.0, companies focus mainly on fulfilling the needs and expectations of their future users. Consumer and business clients' demand, which is mainly influenced by the cost and availability of the technologies, stimulates the design and implementation of new solutions in all three industries. Companies most often implement a selected Industry 4.0 technology at one stage of the product lifecycle. However, it is recognized that the influence and benefits of a single technology spread to other stages, integrating them, and causing a looping effect.

To meet the targets of the UN's Agenda 2030 for Sustainable Development, it is important to put more emphasis on achieving goals and implementing the CE principles by using technology in each industry. The process is difficult, complicated, time-consuming, and capital-intensive. It requires high technological maturity, compatibility between technologies, and adapting them to specific industries and specific needs, and this needs greater expenditure on R&D. The impulses for disseminating different technologies and putting the CE principles into practice should come from the government's development policy, backed up by financial support schemes that promote the use of new technologies. The role of bottom-up and local initiatives cannot be overestimated in this area, as customer demand is the main driver that stimulates supply and production. To direct the manufacturing sector toward the CE solutions, we need to promote and strengthen environmental awareness across the consumer society. Thus, the Refuse principle, which is at the heart of circular rules, is crucial. It is also frequently confirmed by practical examples. Refuse can be practiced at the very beginning of the product lifecycle. The product designer's knowledge of sustainable development and the CE is critical here, as is the consumer's environmental awareness.

The implementation of CE principles is becoming a common objective in the analyzed industries. It can integrate suppliers and users of Industry 4.0 around their efforts to ensure social, environmental, and financial benefits. Noticeably, however, in the light of current conditions, enterprises should focus on more than merely observing the most popular 3R principles through the use of new technologies. In the face of shrinking raw material resources and increases in their prices, companies should take the next step and start implementing the other rules, even though they seem more difficult and complex. To ensure circularity, they require the conscious involvement of the user and close cooperation with enterprises. This means that the incentives that direct companies towards a full transition to the CE framework and the implementation of Industry 4.0 for this purpose should simultaneously target business and society.

Industry 4.0 has recently become one of the vital pillars of the circular economy, contributing to the development of new management concepts such as the CPLC. Industry 4.0 has had a positive impact on the reduction of demand for resources and waste generation, and it also plays an increasingly important role in the development of industries. There is great potential in integrating the activities of PLC participants to achieve synergy effects that are satisfactory for the users. More and more advanced projects lead not only to continuous improvement, but also to further technological innovations. For example, 4D printing, which refers to how products change shape over time, meeting consumer needs, is an evolution of 3D printing technology. Industry 4.0 technologies can contribute to the development of new enterprises emerging based on business models, such as start-ups and spin-off companies across industries.

Moreover, they positively influence the integration of various industries, e.g. cosmetics producers with manufacturers of care devices. In addition, their use in one sector affects sustainability in other sectors. For instance, companies turning to the cloud reduce demand for paper and printing services and the transport needs of their employees. We are convinced that technological projects will increase the integration of different industries in the circular economy of the 21st century. Industries such as cosmetics, medicine, astronautics, construction, and agriculture provide interesting examples today. Currently, however, the use of Industry 4.0 in various industries does not come close to being a universal trend. Therefore, the exchange of knowledge and experience between companies that use Industry 4.0 technologies in accordance with the CE principles, and spreading them across different industries, should remain at the top of the agenda.

When referring to the implications of the presented research results, several issues should be noted. Since the principles of sustainable development and the CE concept increasingly determine the economic development policies of many countries, including restrictive legal regulations based on environmental protection, enterprises should start to intensively prepare for these changes. Today, CE principles in the PLC are a must. Enterprises designing products must consider not only their lifecycle but also circularity. In this regard, there is an urgent need to educate market participants on how to transform linear product lifecycles into circular ones. However, the key challenge seems to be managing a circular product so as to not only obtain an environmental effect, but also to reduce costs in the long term and increase strategic and operational flexibility. It seems that the development and implementation of new technologies have become particularly appropriate in this regard.

Companies offering Industry 4.0 should consider and promote the benefits of their use for the development of the circular economy. Integrating technologies is extremely beneficial because it can foster sustainable effects across the entire CPLC. Companies should more intensively exploit the potential of Industry 4.0 to close product lifecycles. For example, blockchain technology can effectively support the cycle closure opportunities. The greater the scale of the implementation and dissemination of technologies, the lower the total cost of their acquisition and ownership, and the greater their availability, the greater their ability to generate sustainable effects.

ACKNOWLEDGEMENTS

Sections 5.3 and 5.5.3 are the result of the project “Flexibility in relationships with suppliers in terms of supplier-purchaser models of cooperation on product development in the B2B market”, no. 2016/21/B/HS4/00665, financed by the National Science Centre (NCN) in Poland.

REFERENCES

Agarwal, R, Chandrasekaran, S, & Sridhar, M (2016). *Imagining construction's digital future*. McKinsey & Company.

Albornoz, M (2018). https://www.archdaily.com/899599/5-architecture-offices-using-vr-to-present-their-designs (accessed September 14, 2020).

Ali, MM, Rai, R, Otte, JN, & Smith, B (2019). A product life cycle ontology for additive manufacturing. *Computers in Industry*, *105*, 191–203. DOI: 10.1016/j.compind.2018.12.007.

ALICE Technologies. (2020). https://www.alicetechnologies.com/case-studies/ (accessed September 11, 2020).

Allure. (2017). https://www.allure.com/story/kerastase-hair-coach (accessed September 14, 2020).

Ameri, F, & Dutta, D (2005). Product lifecycle management: Closing the knowledge loops. *Computer-Aided Design and Applications*, *2*(5), 577–590. DOI: 10.1080/16864360.2005.10738322

Antikainen, M, Uusitalo, T, & Kivikytö-Reponen, P (2018). Digitalisation as an enabler of circular economy. *Procedia CIRP*, *73*, 45–49. DOI: 10.1016/j.procir.2018.04.027

Asiedu, Y, & Gu, P (1998). Product life cycle cost analysis: State of the art review. *International Journal of Production Research*, *36*(4), 883–908. DOI: 10.1080/002075498193444

Autodesk. (2020). https://damassets.autodesk.net/content/dam/autodesk/www/case-studies/shanghai-tower/shanghai-tower-customer-story.pdf (accessed September 10, 2020).

Bag, S, & Pretorius, JHC (2020). Relationships between technologies 4.0, sustainable manufacturing and circular economy: Proposal of a research framework. *International Journal of Organizational Analysis*. ISSN: 1934-8835. Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/IJOA-04-2020-2120

Becqué, R, Mackres, E, Layke, J, Aden, N, Liu, S, Managan, K, & Graham, P (2016). Accelerating building efficiency: Eight actions for urban leaders. *World Resources Institute, Washington, DC*. ISBN-13: 978-1-56973-887-0.

Below, R, & Wallemacq, P (2018). Annual disaster statistical review 2017. *CRED, Centre for Research on the Epidemiology of Disasters: Brussels, Belgium.*

Benlian, A, Kettinger, WJ, Sunyaev, A, Winkler, TJ Guest Editors. (2018). The transformative value of cloud computing: A decoupling, platformization, and recombination theoretical framework. *Journal of Management Information Systems*, *35*(3), 719–739. DOI: 10.1080/07421222.2018.1481634

Bressanelli, G, Adrodegari, F, Perona, M, & Saccani, N (2018). Exploring how usage-focused business models enable circular economy through digital technologies. *Sustainability*, *10*(3), 639. DOI: 10.3390/su10030639

Cao, H, & Folan, P (2012). Product life cycle: The evolution of a paradigm and literature review from 1950–2009. *Production Planning & Control*, *23*(8), 641–662. DOI: https://10.1080/09537287.2011.577460

Campbell-Johnston, K, ten Cate, J, Elfering-Petrovic, M, & Gupta, J (2019). City level circular transitions: Barriers and limits in Amsterdam, Utrecht and The Hague. *Journal of Cleaner Production*, *235*, 1232–1239. DOI: 10.1016/j.jclepro.2019.06.106

CB Insights. (2019). 15 trends changing the face of the beauty industry in 2020. https://www.cbinsights.com/research/report/beauty-trends-2019/ (accessed September 14, 2020).

Chen, YJ, Chen, YM, & Chu, HC (2009). Development of a mechanism for ontology-based product lifecycle knowledge integration. *Expert Systems with Applications*, *36*(2), 2759–2779. DOI: 10.1016/j.eswa.2008.01.049

Cheniuntai, N (2019). https://www.apis-cor.com/dubai-project (accessed September 9, 2020).

Chiusoli, A (2018). https://www.3dwasp.com/en/3d-printed-house-gaia/ (accessed September 9, 2020).

Cinelli, P, Coltelli, MB, Signori, F, Morganti, P, & Lazzeri, A (2019). Cosmetic packaging to save the environment: Future perspectives. *Cosmetics*, *6*(2), 26. DOI: 10.3390/cosmetics6020026

Cole, R, Stevenson, M, & Aitken, J (2019). Blockchain technology: Implications for operations and supply chain management. *Supply Chain Management: An International Journal*, *24*(4), 469–483. ISSN: 1359-8546.

Colorado, HA, Velásquez, EIG, & Monteiro, SN (2020). Sustainability of additive manufacturing: The circular economy of materials and environmental perspectives. *Journal of Materials Research and Technology*, *9*(4), 8221–8234. DOI: 10.1016/j.jmrt.2020.04.062

Colyer, J (2019). Ashley Furniture transforms factory floor with 3D printing. https://3dprintingindustry.com/news/ashley-furniture-transforms-factory-floor-with-3d-printing-156330/ (accessed September 14, 2020).

Constructech. (2012). https://constructech.com/contractors-adopt-rfid/ (accessed September 14, 2020).

Cosmeticseurope. (2018). Environmental Sustainability: The European Cosmetics Industry's Contribution. https://www.cosmeticseurope.eu/files/9615/2872/3399/CE_Environmental_Sustainability_Report_2018.pdf (accessed September 14, 2020).

Coty (2020). https://www.coty.com/in-the-news/press-release/coty-introduces-blended-reality-beauty-magic-mirror (accessed September 14, 2020).

Darf Design. (2020). https://www.darfdesign.com/mixedrealityvisualisation.html (accessed September 28, 2020).

De Brito, MP, & Dekker, R (2004). A framework for reverse logistics. In *Reverse logistics*. Dekker, R., Fleischmann, M., Inderfurth, K. & Van Wassenhove, L.N. (Eds.) (pp. 3–27). Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-540-24803-3_1

De Sousa Jabbour, ABL, Jabbour, CJC, Godinho Filho, M, & Roubaud, D (2018). Technologies 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations. *Annals of Operations Research*, *270*(1–2), 273–286. DOI: 10.1007/s10479-018-2772-8

Delgado, JMD, Oyedele, L, Beach, T, & Demian, P (2020a). Augmented and virtual reality in construction: Drivers and limitations for industry adoption. *Journal of Construction Engineering and Management*, *146*(7), 04020079. DOI: 10.1061/(ASCE)CO.1943-7862.0001844

Delgado, JMD, Oyedele, L, Demian, P, & Beach, T (2020b). A research agenda for augmented and virtual reality in architecture, engineering and construction. *Advanced Engineering Informatics*, *45*, 101122. DOI: 10.1016/j.aei.2020.101122

Deloitte. (2016). Deloitte sustainability. Circular economy potential for climate change mitigation. https://www2.deloitte.com/content/dam/Deloitte/fi/Documents/risk/Deloitte%20-%20Circular%20economy%20and%20Global%20Warming.pdf (accessed September 15, 2020).

Deloitte. (2019). Point of view on digital construction. The business case of incorporating digital technologies into the construction industry. https://www2.deloitte.com/content/dam/Deloitte/nl/Documents/energy-resources/deloitte-nl-eri-point-of-view-digital-construction.pdf (accessed September 15, 2020).

Den Hollander, MC, Bakker, CA, & Hultink, EJ (2017). Product design in a circular economy: Development of a typology of key concepts and terms. *Journal of Industrial Ecology*, *21*(3), 517–525. DOI: 10.1111/jiec.12610

Design Group Latinamerica. (2020). https://www.dg-la.com/en/home/ (accessed September 16, 2020).

Dubey, R, Gunasekaran, A, Childe, SJ, Papadopoulos, T, Luo, Z, Wamba, SF, & Roubaud, D (2019). Can big data and predictive analytics improve social and environmental sustainability?. *Technological Forecasting and Social Change*, *144*, 534–545. DOI: 10.1016/j.techfore.2017.06.020

Ellen MacArthur Foundation. (2013). Towards the circular economy. *Journal of Industrial Ecology*, *2*, 23–44.

Ellen MacArthur Foundation. (2014). Towards the circular economy. Vol. 3: Accelerating the scale-up across global supply chains.

Ellen MacArthur Foundation. (2015). Towards a circular economy: Business rationale for an accelerated transition.

Ellen MacArthur Foundation. (2017) https://www.ellenmacarthurfoundation.org/assets/galleries/CEinaction-_Activity06-nine-Rs-6R3_from-graham-081217.pdf (accessed September 6, 2020).

Ellen MacArthur Foundation. (2019a). *Circular economy in cities*. Project Guide.

Ellen MacArthur Foundation. (2019b). Introduction to the circular economy.

Ellen MacArthur Foundation. (2020). Ahrend bringing office furniture full circle.

Esmaeilian, B, Sarkis, J, Lewis, K, & Behdad, S (2020). Blockchain for the future of sustainable supply chain management in Technologies 4.0. *Resources, Conservation & Recycling*, *163*, 105064. DOI: 10.1016/j.resconrec.2020.105064

eSUB. (2020). eSUB construction software. https://esub.com/case-study-pico-volt/, https://esub.com/case-study-ground-breakers-construction/ (accessed September 14, 2020).

European Commission. (2014). COM(2014) 398 final/2. *Towards a Circular Economy: A Zero Waste Programme for Europe*.

European Commission. (2015). COM(2015) 614 final. *Final—Closing the Loop—An EU Action Plan for the Circular Economy*.

European Commission. (2020). COM(2020) 98 final. *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*.

European Environment Agency (EEA). (2016). Circular economy in Europe developing the knowledge base. *EEA*. ISBN-13: 978-92-9213-719-9.

European Environment Agency (EEA). (2017). Circular by design – Products in the circular economy. *EEA*. Report No 6/2017. ISBN-13: 978-92-9213-857-8.

European Investment Bank. (2020). The EIB circular economy guide supporting the circular transition. *EIB*. DOI: 10.2867/578286. ISBN-13: 978-92-861-4672-5.

Fidelis, M, de Moura, C, Kabbas Junior, T, Pap, N, Mattila, P, Mäkinen, S, Putnik P, Granato, D, Bursac Kovacevic D, Tian Y, and Yang B (2019). Fruit seeds as sources of bioactive compounds: Sustainable production of high value-added ingredients from by-products within circular economy. *Molecules*, *24*(21), 3854. DOI: 10.3390/molecules24213854

Forrest, A, Hilton, M, Ballinger, A and Whittaker, D (2017). Circular economy opportunities in the furniture sector. *European Environmental Bureau: Brussels, Belgium*. https://eeb.org/library/circular-economy-opportunities-in-the-furniture-sector/ (accessed September 13, 2020).

Fortunati, S, Martiniello, & L. Morea, D (2020). The strategic role of the corporate social responsibility and circular economy in the cosmetic industry. *Sustainability, 12*(12), 5120. DOI: 10.3390/su12125120

GASHU Arquitectos. (2020). https://gashuarquitectos.com/servicios/ (accessed September 28, 2020).

Ge, X, & Jackson, J (2014). The big data application strategy for cost reduction in automotive industry. *SAE International Journal of Commercial Vehicles*, *7*(2014-01-2410), 588–598. DOI: 10.4271/2014-01-2410

Ginga, CP, Ongpeng, JMC, Daly, M, & Klarissa, M (2020). Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials*, *13*(13), 2970. DOI: 10.3390/ma13132970

Herman Miller. (2020). 3D models and planning tools. https://www.hermanmiller.com/en_apc/resources/3d-models-and-planning-tools/ (accessed September 12, 2020).

Head & Shoulders. (2020). https://www.headandshoulders.ca/en-ca/whats-new/new-head-shoulders-bottle-to-be-made-with-recycled-beach-plastic (accessed September 14, 2020).

HiMirror. (2020). https://www.himirror.com/en-US/eshop/product/HiMirrorSlide (accessed September 14, 2020).

HISER project. (2020). http://hiserproject.eu/index.php/our-activities/smart-demolitions-and-refurbishments (accessed September 9, 2020).

Hodgson, P, & Brooks, P (2018). Tata steel Europe's approach to the circular economy in a life cycle perspective. *Asian Steel Watch*, *5*, 24–33.

Iles, J (2018). Brands team up to see how 3D printing can revolutionise repair. https://medium.com/circulatenews/brands-team-up-to-see-how-3d-printing-can-revolutionise-repair-86d882d2a95d (accessed September 8, 2020).

INCOSE UK. (2017). Guide to lifecycles and lifecycle models issue 1.1 https://webcache.googleusercontent.com/search?q=cache:qrR1SN98Z-0J:https://www.apm.org.uk/media/13835/guide-to-lifecycle-models.pdf+&cd=1&hl=pl&ct=clnk&gl=pl&client=firefox-b-d (accessed September 10, 2020).

Institution of Civil Engineers. (2018). Blockchain technology in the construction industry. *Digital Transformation for High Productivity*. https://www.ice.org.uk/ICEDevelopmentWebPortal/media/Documents/News/Blog/Blockchain-technology-in-Construction-2018-12-17.pdf (accessed September 11, 2020).

International Organization for Standardization. (2006). *Environmental management: Life cycle assessment; Principles and framework* (No. 2006). ISO.

IPCC Working Group I. (2013). *Climate Change 2013: The Physical Science Basis: Summary for Policymakers*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/03/WG1AR5_SummaryVolume_FINAL.pdf (accessed August 20, 2020). ISBN-13: ISBN 978-92-9169-138-8. DOI: 10.1017/CBO9781107415324

Ishii, K, Eubanks, CF, & Di Marco, P (1994). Design for product retirement and material lifecycle. *Materials & Design*, *15*(4), 225–233. DOI: 10.1016/0261-3069(94)90007-8

Jin, R, Yuan, H, & Chen, Q (2019). Science mapping approach to assisting the review of construction and demolition waste management research published between 2009 and 2018. *Resources, Conservation and Recycling*, *140*, 175–188. DOI: 10.1016/j.resconrec.2018.09.029

Johnson Controls. (2015). https://g2electrical.co.uk/wp-content/uploads/2018/03/be_case_study_cisco.pdf (accessed September 14, 2020).

Kang, HS, Lee, JY, Choi, S, Kim, H, Park, JH, Son, JY, … & Do Noh, S (2016). Smart manufacturing: Past research, present findings, and future directions. *International Journal of Precision Engineering and Manufacturing-green Technology*, *3*(1), 111–128. DOI: 10.1007/s40684-016-0015-5

Kellens, K, Baumers, M, Gutowski, TG, Flanagan, W, Lifset, R, & Duflou, JR (2017). Environmental dimensions of additive manufacturing: Mapping application domains and their environmental implications. *Journal of Industrial Ecology*, *21*(S1), S49–S68. DOI: 10.1111/jiec.12629

Kiritsis, D (2011). Closed-loop PLM for intelligent products in the era of the Internet of things. *Computer-Aided Design*, *43*(5), 479–501. DOI: 10.1016/j.cad.2010.03.002

Kondoh, S, Tateno, T, Kishita, Y, Komoto, H, & Fukushige, S (2017). The potential of additive manufacturing technology for realizing a sustainable society. In *Sustainability through innovation in product life cycle design*. Matsumoto, Mitsutaka, Masui, Keijiro, Fukushige, Shinichi, & Kondoh, Shinsuke (Eds.) (pp. 475–486). Springer, Singapore.

Korhonen, J, Nuur, C, Feldmann, A, & Birkie, SE (2018). Circular economy as an essentially contested concept. *Journal of Cleaner Production*, *175*, 544–552. DOI: 10.1016/j.jclepro.2017.12.111

Kristoffersen, E, Blomsma, F, Mikalef, P, & Li, J (2020). The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *Journal of Business Research*, *120*, 241–261. DOI: 10.1016/j.jbusres.2020.07.044

Kumar, S (2005). Exploratory analysis of global cosmetic industry: Major players, technology and market trends. *Technovation*, *25*(11), 1263–1272. DOI: 10.1016/j.technovation.2004.07.003

Kurilova-Palisaitiene, J, Lindkvist, L, & Sundin, E (2015). Towards facilitating circular product life-cycle information flow via remanufacturing. *Procedia Cirp*, *29*, 780–785. DOI: 10.1016/j.procir.2015.02.162

Lacy, P, Long, J and Spindler, W (2020). How can businesses accelerate the transition to a circular economy? https://www.weforum.org/agenda/2020/01/how-can-we-accelerate-the-transition-to-a-circular-economy/ (accessed September 10, 2020).

Lancôme. (2020). https://www.lancome-usa.com/le-teint-particulier/LAN233.html (accessed September 14, 2020).

Leng, J, Ruan, G, Jiang, P, Xu, K, Liu, Q, Zhou, X, & Liu, C (2020). Blockchain-empowered sustainable manufacturing and product lifecycle management in technologies 4.0: A survey. *Renewable and Sustainable Energy Reviews*, *132*, 110112. DOI: 10.1016/j.rser.2020.110112

Lindkvist, L, Movilla, NA, Sundin, E, & Zwolinski, P (2017). Investigating types of information from WEEE take-back systems in order to promote Design for Recovery. In *Sustainability through innovation in product life cycle design*. Matsumoto, Mitsutaka, Masui, Keijiro, Fukushige, Shinichi, & Kondoh, Shinsuke (Eds.) (pp. 3–19). Springer, Singapore. DOI: 10.1007/978-981-10-0471-1_1

Łopaciuk, A, & Łoboda, M (2013, June). Global beauty industry trends in the 21st century. In *Management, Knowledge and Learning International Conference* (pp. 19–21).

L'Oréal. (2018). Progress report, Sharing beauty with all. https://www.loreal-finance.com/en/annual-report-2018/responsibility-1–5/ (accessed September 14, 2020).

L'Oréal. (2020a). https://www.loreal.com/en/news/group/how-is-digital-transformation-helping-loreal-work-wonders/ (accessed September 14, 2020).

L'Oréal. (2020b). https://www.lorealparisusa.com/beauty-magazine/makeup/makeup-looks/makeup-genius-from-day-to-night.aspx (accessed September 14, 2020).

Lourenço-Lopes, C, Fraga-Corral, M, Jimenez-Lopez, C, Pereira, AG, Garcia-Oliveira, P, Carpena, M, … & Simal-Gandara, J (2020). Metabolites from macroalgae and its applications in the cosmetic industry: A circular economy approach. *Resources*, *9*(9), 101. DOI: 10.3390/resources9090101

Love that Design. (2020). Technology disrupts the furniture manufacturing industry. https://www.lovethatdesign.com/article/technology-disrupts-the-furniture-manufacturing-industry/ (accessed September 10, 2020).

LuluLab. (2020). http://www.lulu-lab.com/en/ (accessed September 14, 2020).

Manyika, J, Chui, M, Bisson, P, Woetzel, J, Dobbs, R, Bughin, J, & Aharon, D (2015). *Unlocking the potential of the Internet of Things*. McKinsey & Company. https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/the-internet-of-things-the-value-of-digitizing-the-physical-world (accessed September 15, 2020).

Mink. (2020). https://www.minkbeauty.com/products/mink-makeup-printer (accessed September 14, 2020).

Moreno, M, & Charnley, F (2016). Can redistributed manufacturing and digital intelligence enable a regenerative economy? An integrative literature review. In *Sustainable design and manufacturing*. Scholz, Steffen G., Howlett, Robert J., & Setchi, Rossi (Eds.) (pp. 563–575). Springer, Cham. DOI: 10.1007/978-3-319-32098-4_48

Morseletto, P (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*, 104553. DOI: 10.1016/j.resconrec.2019.104553

Nascimento, DLM, Alencastro, V, Quelhas, OLG, Caiado, RGG, Garza-Reyes, JA, Rocha-Lona, L, & Tortorella, G (2019). Exploring Technologies 4.0 to enable circular economy practices in a manufacturing context. A business model proposal. *Journal of Manufacturing Technology Management*, *30*, 607–627. DOI: 10.1108/JMTM-03-2018-0071

NBS. 2020. 10th Annual BIM Report (2020). https://www.thenbs.com/knowledge/national-bim-report-2020 (accessed September 21, 2020).

Nowy Styl. (2020). https://nowystyl.com/en/competences/technology/ (accessed September 15, 2020).

Okorie, O, Salonitis, K, Charnley, F, Moreno, M, Turner, Ch., & Tiwari, A (2018). Digitalisation and the circular economy: A review of current research and future trends. *Energies*, *11*, 1–33. DOI: 10.3390/en11113009.

Opalis. (2020). https://opalis.eu/fr/projets/vla-architecture (accessed September 10, 2020).

Ozkan, NN (2015). An example of open innovation: PG. *Procedia-Social and Behavioral Sciences*, *195*,1496–1502. DOI: 10.1016/j.sbspro.2015.06.450

Pagoropoulos, A, Pigosso, DC, & McAloone, TC (2017). The emergent role of digital technologies in the circular economy: A review. *Procedia CIRP*, *64*, 19–24. DOI: 10.1016/j.procir.2017.02.047.

Parlikad, AK, McFarlane, D, Fleisch, E, & Gross, S (2003). The role of product identity in end-of-life decision making, White paper. *Auto-ID Center*, Institute for Manufacturing, Cambridge, 1–26.

Piscitelli, G, Ferazzoli, A, Petrillo, A, Cioffi, R, Parmentola, A & Travaglioni, M (2020). Circular economy models in the technologies 4.0 era: a review of the last decade. *Procedia Manufacturing*, *42*, 227–234. DOI: 10.1016/j.promfg.2020.02.074

Polcom. (2020). Farmona stawia na cloud computing w Polcom Data Center, case study. https://polcom.com.pl/newsroom/laboratorium-kosmetykow-naturalnych-farmona-stawia-na-chmure (accessed September 12, 2020).

Potting, J, Hekkert, MP, Worrell, E, & Hanemaaijer, A (2017). *Circular economy: Measuring innovation in the product chain* (p. 2544). PBL Publishers, The Hague.

Procter & Gamble. (2019). Environmental sustainability 2019. https://us.pg.com/sustainability-reports/ (accessed September 12, 2020).

Procter & Gamble. (2020). https://www.pgconnectdevelop.com/ (accessed September 14, 2020).

Rajput, N (2019). Cosmetics market by category (skin sun care products, hair care products, deodorants, makeup color cosmetics, fragrances) and by distribution channel (general departmental store, supermarkets, drug stores, brand outlets) – Global opportunity analysis and industry forecast, 2014–2022. [online] Allied Market Research. https://www.alliedmarketresearch.com/cosmetics-market (accessed September 14, 2020).

Rajput, S & Singh, SP (2019). Connecting circular economy and technologies 4.0. *International Journal of Information Management*, *49*, 98–113. DOI: 10.1016/j.ijinfomgt.2019.03.002

Reike, D, Vermeulen, WJ, & Witjes, S (2018). The circular economy: New or refurbished as CE 3.0?—Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264. DOI: 10.1016/j.resconrec.2017.08.027

Reuter, MA (2016). Digitalizing the circular economy: Circular economy engineering defined by the metallurgical internet of things. *Metallurgical and Materials Transactions B*, *47*, 3194–3220. DOI: 10.1007/s11663-016-0735-5

Rizos, V, Tuokko, K, & Behrens, A (2017). *The circular economy: A review of definitions, processes and impacts (No. 12440)*. Centre for European Policy Studies. https://www.researchgate.net/publication/315837092_The_Circular_Economy_A_review_of_definitions_processes_and_impacts (accessed September 8, 2020). ISBN-13: 978-94-6138-597-0.

Rose, CM, Ishii, K, & Stevels, A (2002). Influencing design to improve product end-of-life stage. *Research in Engineering Design*, *132*, 83–93.

Rosa, P, Sassanelli, C, Urbinati, A, Chiaroni, D, & Terzi, S (2019). Assessing relations between circular economy and technologies 4.0: A systematic literature review. *International Journal of Production Research*, *58*(6), 1662–1687. DOI: 10.1080/00207543.2019.1680896

Saaksvuori, A, & Immonen, A (2008). *Product lifecycle management*. Springer Science Business Media, Berlin, Heidelberg. ISBN-13: 978-3-540-78172-1.

Sage Construction and Real Estate. (2015). Cloud computing and the construction industry. https://www.teamtag.net/wp-content/uploads/2015/07/Sage-CRE-Whitepaper-Cloud-Computing-and-the-Construction-Industry.pdf (accessed September 15, 2020).

Seebacher, S & Schüritz, R (2017). Blockchain technology as an enabler of service systems: A structured literature review. *Eighth International Conference on Exploring Service Science*, *IESS 1.7*. https://www.researchgate.net/publication/315858662_Blockchain_Technology_as_an_Enabler_of_Service_Systems_A_Structured_Literature_Review (accessed September 12, 2020). DOI: 10.1007/978-3-319–56925-3_2

Slaughter, P (2018). Blockchain: Could it be supply chain game changer? https://www.furnituretoday.com/business-news/blockchain-could-it-be-supply-chain-game-changer/ (accessed September 14, 2020).

Srai, JS, Kumar, M, Graham, G, Philips, W, Tooze, J, Ford, S, Beecher, P, Raj, B, Gregory, M, Tiwari, MK, Ravi, B, Neely, A, Shankar, R, Charnley & Tiwari, A (2016). Distributed manufacturing: Scope, challenges and opportunities. *International Journal of Production Research*, *54*, 6917–6935. DOI: 10.1080/00207543.2016.1192302

Stark, J (2016). Product lifecycle management. In *Product lifecycle management volume 2*. Stark, John (Eds.) (pp. 1–35). Springer, Cham. ISBN-13: 978-3-319-24436-5.

Sukhdev, A, Vol, J, Brandt, K, & Yeoman, R (2018). *Cities in the circular economy: the role of digital technology*. Ellen MacArthur Foundation, Cowes, UK. https://www.ellenmacarthurfoundation.org/assets/downloads/Cities-in-the-Circular-Economy-The-Role-of-Digital-Tech.pdf (accessed September 14, 2020).

Suoza, E (2019). https://www.archdaily.com/914501/9-augmented-reality-technologies-for-architecture-and-construction (accessed September 11, 2020).

Terzi, S, Bouras, A, Dutta, D, Garetti, M, & Kiritsis, D (2010). Product lifecycle management–from its history to its new role. *International Journal of Product Lifecycle Management*, *44*, 360–389. DOI: 10.1504/IJPLM.2010.036489

Tóth Szita, K (2017). The application of lifecycle assessment in circular economy. *Hungarian Agricultural Engineering*, *31*, 5–9. DOI: 10.17676/HAE.2017.31.5

United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development. https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf (accessed September 20, 2020).

Urie, M (2019). The Internet of things in construction. https://marketintel.gardiner.com/uploads/1901_IoT-in-Construction.pdf (accessed September 15, 2020).

Vermeulen, WJV, Reike, D, & Witjes, S (2018). Circular economy 3.0: Getting beyond the messy conceptualization of circularity and the 3R's, 4R's and more …. https://www.cec4europe.eu/wp-content/uploads/2018/09/Chapter-1.4._W.J.V.-Vermeulen-et-al._Circular-Economy-3.0-getting-beyond-the-messy-conceptualization-of-circularity-and-the-3Rs-4-Rs-and-more.pdf (accessed September 8, 2020).

Wingtra. (2020). https://wingtra.com/case_studies/wingtraone-estonian-road-survey/ (accessed September 14, 2020).

World Economic Forum. (2019). https://www.weforum.org/press/2019/10/seven-mining-metals-companies-partner-on-responsible-sourcing-with-world-economic-forum (accessed September 21, 2020).

World Economic Forum. (2020). https://intelligence.weforum.org/topics/a1Gb0000000pTDMEA2?tab=publications (accessed September 12, 2020).

Wortmann, F, & Flüchter, K (2015). Internet of things: Technology and value added. *Business & Information Systems Engineering*, *57*(3), 221–224. DOI: 10.1007/s12599-015-0383-3

Young, RI, Gunendran, AG, Cutting-Decelle, AF, & Gruninger, M (2007). Manufacturing knowledge sharing in PLM: A progression towards the use of heavy weight ontologies. *International Journal of Production Research*, *457*,1505–1519. DOI: 10.1080/00207540600942268

Zhong, RY, Xu, X, Klotz, E & Newman, ST (2017). Intelligent manufacturing in the context of Technologies 4.0: A review. *Engineering*, *3*, 616–630. DOI: 10.1016/J.ENG.2017.05.015

Zink, T, & Geyer, R (2017). Circular economy rebound. *Journal of Industrial Ecology*, *213*, 593–602. DOI: 10.1111/jiec.12545