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The 9th CIRP IPSS Conference: Circular Perspectives on Product/Service-Systems

## The emergent role of digital technologies in the Circular Economy: A review

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### Abstract

Digital technologies have enabled the formulation of multiple Product Service-Systems (PSS) with considerable economic, environmental and societal benefits. One of the most promising paradigms, which is inspired by business models and value propositions that have already been described in the PSS literature, is the concept of Circular Economy. Circular Economy is characterized as an economy that is restorative and regenerative by design and is attracting significant attention from researchers and policy makers alike. In light of the recent proliferation of digital technologies such as Big Data and the Internet of Things, this article attempts to identify how can digital technologies support the transition to Circular Economy. This article conducted a systematic review of the literature based on a review protocol, in an effort to evaluate the application of key digital technologies in Circular Economy. The study concludes by identifying research gaps, reflecting on the application of digital technologies in the field of PSS and proposing suggestions for future research.

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*Keywords:* Circular Economy; digital technologies; digitization; Product/Service-Systems

### 1. Introduction

Currently, manufacturing companies are driven by a search for enhanced revenue based on sales volume and cost reduction in supply chains, factories and operations. In the current linear economy, based on a “take-make-dispose” philosophy, products are increasingly becoming commodities, and resource scarcity is becoming a reality for a large variety of materials. In order to remain competitive in this economic context, companies are increasingly looking for alternative ways to achieve sustainable growth and enhanced resource efficiency. Over the last years, various consumption practices that challenge the established growth paradigm, based on a linear economy, have been proposed.

One of the most promising paradigms to appear in recent years is the Circular Economy. According to the Ellen MacArthur Foundation, the Circular Economy is characterized as an economy that is restorative and

regenerative by design and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles [1]. In a Circular Economy, companies concentrate on rethinking products and services from the bottom up to “future proof” their operations and prepare for inevitable resource constraints – all the way through to the customer value proposition [2].

In many cases, the implementation of Circular Economy in manufacturing companies requires changes in their business models, which can be achieved by means of Product/Service-Systems (PSS). PSS is one particular value proposition that has attracted considerable attention over the past few decades as a way to decouple economic growth from resource consumption. PSS promote a focus shift from selling just products to selling the utility, through a mix of products and services while fulfilling the same client demands with less environmental impact [3].

One can draw multiple similarities between PSS and Circular Economy. Both advocate the focus on fulfilling the needs of the users in an effort to radically lower environmental impacts [4], [5]. Moreover, they are characterized by a high degree of overlap as, according to [4], many of the most promising PSS business models are circular in nature. At the same time though, PSS might lead to inefficient practices and less circular models, most notably through rebound effects [6].

While not entirely the same, the commonalities between Circular Economy and PSS invite a deeper investigation into Circular Economy from a PSS perspective. In both PSS and Circular Economy, information technologies play a critical role [4], [7], [8]. The Ellen McArthur Foundation acknowledges the role of intelligent assets and connectivity in the proliferation of Circular Economy [1]. Despite their promise though, there is a limited knowledge as to how new digital technologies and capabilities such as the Internet of Things (IoT) and Big Data can be leveraged to support the transition to Circular Economy. This study attempts to close this gap by conducting a systematic literature review, in order to evaluate the application of digital technologies to support the transition to Circular Economy. Therefore, it poses the following research question:

RQ: How can digital technologies support the transition to a Circular Economy?

The next section presents the research methodology, and is followed by the presentation of the obtained results. Conclusions and future work are discussed in Section 4.

**2. Research methodology**

*2.1 Data collection*

A systematic literature review was conducted to examine the intersection between digital technologies and digital capabilities and Circular Economy. The research methodology was based on [9] in an effort to provide a replicable process, and limit the bias of the research.

In order to identify the relevant studies that lie at the intersection between Circular Economy and digital technologies, we used keywords –shown in Appendix A- to query online databases, namely Scopus and Web of Science. The review was carried out in a three-step process, as shown in Fig. 1 consisting of three steps: Collection, Evaluation, and Analysis. During A total of 135 studies were identified, which were reduced to 33 articles after checking the abstract and its contents for relevance. After reading the articles and including articles from the secondary analysis of citations, only 12 were retained.

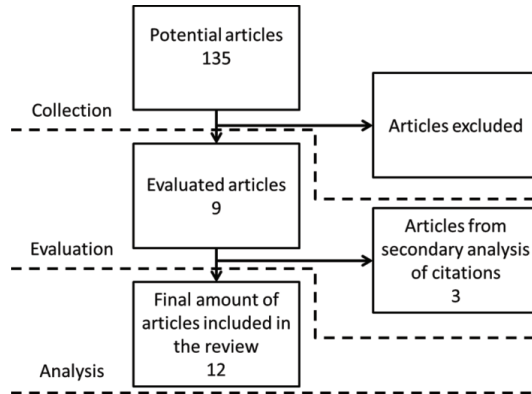


Fig. 1. Systematic review process

*2.2 Data analysis*

To systematically analyze the identified studies, a review protocol was used (see Appendix A). The review protocol specifies the central research question, and helps evaluate the studies based on predefined data extraction forms. The use of data extraction forms helps standardize the way information is collected and analyzed by the researchers [9]. The coding scheme consists of four categories as shown in Fig. 2.

- Study type: Evaluate whether the study is a review summarizing the literature on a specific topic, a case study illustrating the application of digital technologies in Circular Economy, or a conceptual study proposing a framework.
- Life cycle stages: Identify the life cycle phases that the study attempts to cover.
- Digital technologies: Identify the technologies that are associated to the Circular Economy.
- Digital architecture perspective: includes three data architectural layers [10], as shown in Fig. 2.
  - Data collection: focus on the collection of data from various sources and Systems of Records (SOR).
  - Data integration: covers technologies that assist with the transformation, integration and maintenance of data.
  - Data analysis: focuses on technologies that assist in extracting business value through the analysis of data.

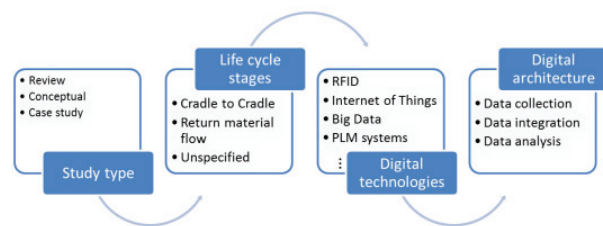


Fig. 2. Coding scheme dimensions and indicative categories

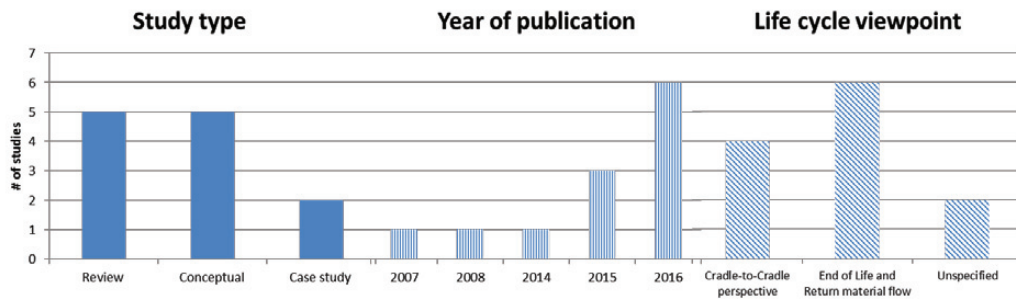


Fig. 3. Overview of identified literature in terms of Study type, Year of publication and Life cycle viewpoint

### 3. Results

#### 3.1. Reviewed studies typology

This section summarizes the application of the identified digital technologies in the transition towards Circular Economy, as identified through the literature review. Fig. 3 illustrates the results of the classification.

The intersection between digital technologies and Circular Economy is a meager but fast growing area, as evident from the limited amount of relevant studies and the fact that the majority studies were published after 2014. So far, the growing literature on the Circular Economy relies on studies and concepts from adjacent research fields such as PSS, industrial ecology and green supply chain logistics. Interestingly, the majority of the studies are either conceptual or reviews, as there is a limited amount of quantitative case studies evaluating the application of digital technologies in the context of the Circular Economy. One can argue that the field is still in a pre-paradigmatic phase, with Circular Economy discussed together with other concepts such as decentralized manufacturing [11], [12] and enterprise systems [13], [14].

#### 3.2. Application of digital technologies

The following sections are limited to the key technologies identified throughout the review process. This is due to the fact that some of the identified digital technologies (e.g. ERP systems or sensors) have either received attention from a single study, or their connection and impact to Circular Economy is not clearly established in the literature. Fig. 4 illustrates the grouping of the technologies that were discussed in literature, according to the three architectural layers.

##### 3.2.1 Data collection

**Radio Frequency Identification (RFID):** a data collection technology that has attracted significant attention within the context of Circular Economy. RFID uses electromagnetic fields to automatically identify and track tags attached to object. In the context of circular economy, RFID help track material flows to enable value recovery through the

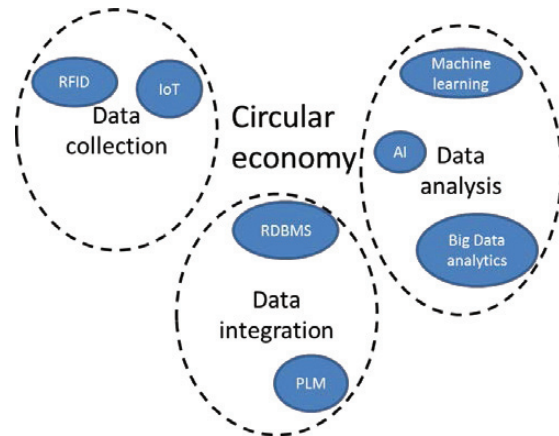


Fig 4. Grouping of digital technologies according to three architectural layers

implementation of Re-strategies such as Reuse, Repair and Remanufacture. In their review of Reverse Logistics and Closed Supply Chains, Govindan et al [15] argue that information technology and collaboration can play a critical role, as RFID facilitate the transition to closed-loop systems. Moreover, according to [16], networked RFID systems help connect products tagged with an RFID chip to an information network, providing complete information about the product's life cycle to all networked partners.

**Internet of Things (IoT):** defined as sensors and actuators connected by networks to computing systems that can monitor or manage health and actions of connected objects and machines [17]. In the context of Circular Economy, IoT can collect information generated by sensors to connect stakeholders across the value chain. In the review of digitalization of Circular Economy, and its importance for the field of metallurgy, Reuter [18] argues that IoT can help describe Circular Economy models as dynamic feedback control loops. Moreover, IoT provides a fundamental basis for evaluating the consequences if the actions of various stakeholders throughout the life of the physical products. Furthermore, Salminen et al. [19] corroborate the importance of IoT. The authors highlight the importance of IoT for Circular Economy, as management and analysis of data coming from various sources is routed through data-to-service

process, leading to business co-evolution of Circular Economy.

### 3.2.2 Data Integration

*Relational Database Management Systems (RDBMS) and database handling systems:* systems associated with the organization of data in formally described tables. They allow the integration of heterogeneous data sources, by specifying a data architecture to enable the analytical requirements of the information architecture [10]. Due to the proliferation of digital technologies and the exponential increase in the volume of data that is being produced [1], recognizing and using the valuable information that is scattered around the organization is a key business challenge [20]. RDBMS and data handling systems support the goals of Circular Economy, as they integrate the wealth of information produced by heterogeneous data collection systems such as IoT, ERP and CRM systems. In regard to adaptive calibration of fuel injection and combustion processes, Ge and Jackson [21] argue that parallel RDBMS infrastructure can support adaptive calibration processes. Salminen et al. [19] highlight the role of data standardization and warehousing in waste handling, as it facilitates decision making leading to the re-planning of the value network. Yet despite their importance, the description of role, complexity and technical requirements of such systems is often downplayed, with only a few studies acknowledging their influence on successful implementation of Circular Economy.

*Product Lifecycle Management (PLM) systems:* information management systems that can integrate data, processes, business systems and, ultimately, people in an extended enterprise. PLM systems support the transition to the Circular Economy, as they help integrate information across multiple life cycles and across various stakeholders in the value chain. Lieder et al. [22] highlight the importance of PLM systems in the company level, as they enable monitoring of products and parts in multiple lifecycles. The authors argue for the definition of a product passport, i.e. a set of information about the components and materials that a product contains, and how they can be disassembled and recycled at the end of the product's useful life". In their multiple case study analysis, Srari et al [12] highlight the importance of data integration opportunities that information systems normally enable. In particular, PLM systems enable near time consumption and optimization of stock and material flows.

### 3.2.3. Data Analysis

*Machine learning:* practice based on algorithms that can learn from data without relying on rules-based programming. Also referred to as Artificial Intelligence (AI), the application of machine learning algorithms such as Neural Networks that rely on mass processing of data, rather than a complex set of rules to identify patterns in the data and make predictions. Machine learning can be applied in the context of Circular Economy to support process and system optimization based on the huge amount of data. Weichart et al [13] argue that the use of Artificial Intelligence (AI) tools and techniques for designing intelligent enterprise systems leverages the next era of computing theory and applications towards circular

business models. Reuter [18] proposes the use of AI in the field of metallurgy to analyze and control industrial metallurgical systems and processes.

*Big Data analytics:* consequence of the increase of technical data collection capacity, due to the proliferation of inexpensive processing equipment, resulting in increase of the size of datasets. Big Data is characterized by the four V's: Volume, Velocity, Variety and Veracity. As a result, Big Data sets are too large and rapidly changing to be analyzed using traditional database techniques or commonly used software tools [23]. Within the context of Circular Economy, Big Data analytics is seen as a viable approach to make use of information from various systems of record such as sensors and IoT, to enable better decision making. It should be noted that Big Data is not always discussed as a concept directly, but rather as an approach to analyze a high volume of data, originating from different data sources. For example, Ge and Jackson [21] discuss the opportunities of Big Data for the automotive industry, and exemplify the efficacy through three case studies: internal combustion engine maintenance, spare part reuse and engine remanufacturing. The authors argue that Big Data can integrate lifelong information and enable the implementation of new strategies. In the context of the manufacturing industry, Lieder et al. [22] argue that real time data analytics can enable decision making for adaptive calibration. Srari et al. [12] argue that data analytics that can provide insights both from raw data and also embedded data on multiple machine/equipment/product objects. Based on a review of 33 case studies focused on the application of circular innovation, Moreno and Charnley [11] highlight the capabilities of Big Data to monitor processes of production and consumption, that eventually allow material flows to be closed easily.

### 3.3. Overall reflections on the state of literature and the role of digital technologies

The areas of data collection and data analysis are often discussed together, with particular focus on the interplay between Internet of Things (IoT) and Big Data analytics [4], [12], [14], [18]. In contrast, the role of data integration is either implicit or not discussed at all in those studies. The value proposition of data integration systems in the context of Circular Economy is not clear, i.e. we do not know how to use the data to support transition to less linear and more circular business models. A notable exception is the work by Ge and Jackson [21], on the application of Big Data in the automotive industry. The authors discuss the opportunities of applying Big Data in two cases, particularly in the remanufacturing of engines and injection control. Big Data is not discussed in isolation, but rather in relation to other digital technologies for data handling and analysis such as RDBMS and Distributed File Systems (DFS).

Data integration -and more broadly the data architecture and its capabilities- is an indispensable part of business applications, as it bridges the individual information sources to the business goals of the involved stakeholders and their application in day-to-day business. Moreover, it is a resource

intensive step, as data preparation and integration is usually between 60 and 75% of the project time [10]. Conclusively, given the importance of the underlying data architecture and data integration infrastructure in connecting the collected information to the goals of the Circular Economy, we believe that this is an important gap in the literature.

There is a general agreement that digital technologies play an important role in the transition towards a more circular – and less linear- economy. And although their importance is not contested, the maturity level of digital technologies is disputed. According to [22] Information Technologies seem sufficiently mature to support Circular Economy implementation at large scale. Other studies are more cautious. In his review of circular business model design, Lewandowski [4] argues that it is important to consider how digital technologies can use adequate IT and data management technologies to support material tracking and other specific technologies e.g recycling. This limitation might be related to the lack of business perspective in the literature. According to Lieder and Rashid [22] an important gap in evaluating Circular Economy is the fact that most studies neglect business and economic perspectives. This limitation naturally extends to the evaluation of digital technologies within Circular Economy. Two notable exceptions to this norm are the works by Ge and Jackson [21] and Jayaraman et al. [16].

Lastly, in regard to life cycle stages, digital technologies can help close the material loop, so the primary focus is on the End of Life (EoL) and link to production. One notable example is the use of RFIDs, which can contain valuable information on how the product was utilized by the customer. As this information can be used to estimate the quality level (s) of the return, the increased transparency and efficiency can facilitate the integration of return flows into the forward flows [24]. Moreover, in his review of digitizing the Circular Economy for metallurgy, Reuter [18] argues that by linking industrial compositional data of the EoL products to their behavior in process metallurgical reactors, Big Data can be used to calibrate the simulation, optimization and dynamic models, thus leading to higher recovery rates. Other studies focus on the optimization potential from digital technologies. For example, Srari et al. [12] argue that connected manufacturing can enable monitoring, control, and optimization of stocks and material flows cooperation and communication over processes and networks in order to achieve the optimum localized manufacturing output to meet city demand.

#### 4. Conclusions and future work

The present study tried to answer the following research question:

RQ: How can digital technologies support the transition to a Circular Economy?

Through a systematic literature review based on a coding scheme, we identified seven main technologies, grouped

under three architecture perspectives (data collection, data analysis and data integration). The present results show that the intersection of Circular Economy and digital technologies is a small, but fast growing research area that is still in a pre-paradigmatic stage, as it is still adopting concepts from other fields and is lacking concrete case studies. Studies have diverging views on the maturity of digital technologies and the life cycle stages, where digital technologies can play a role. In conclusion, despite the disparities across the identified studies, digital technologies play an important role in the transition towards a Circular Economy by optimizing forward material flows and enabling reverse material flows. In that regard, Circular Economy is following a similar trajectory with PSS and service ecosystems in general, where digital technologies have been a critical enabler [25]–[27]. Reflecting on PSS, digital technologies that have only recently being introduced like IoT and Big Data have a strong potential, and can help develop PSS that are environmentally benign [6]

The main identified gap in this study is the limited technological perspective, as the interplay between data collection, data integration, and data analysis is well understood. In the future, researchers should focus on this gap, and also create more empirical results, by evaluating the application of digital technologies in actual case studies.

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#### Appendix A. Search keywords

ALL ( "Circular economy" ) AND TITLE-ABS-KEY ( "digital" ) OR TITLE-ABS-KEY ( "digitization" ) OR TITLE-ABS-KEY ( "digitalization" ) OR TITLE-ABS-KEY ( "digital technologies" )

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