A new productive model of circular economy enhanced by digital transformation in the Fourth Industrial Revolution - An integrated framework and real case studies

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Abstract: The socio-economic trends in the last decades (population growth, rapid industrialization and urbanization) have accelerated the transition from the old linear material flow to the more sustainable circular economy (CE). CE is recognized as a clear value creation opportunity, which can bring the lasting benefits of a more innovative, resilient and productive economy. Nevertheless, there is a huge gap between the big concept of CE and the practical actions. In particular, the research and the implementation of circular models to date have mainly focused on the product end-of-life, in order to reduce, reuse and recycle waste, but the lack of feedback information and performance indexes does not allow the measurement of how a product, a process or a company is really transiting from linear to circular models. This critical issue limits the further development of other circular activities. The impending digital transformation within the 'Fourth Industrial Revolution' can support CE to provide these missing aspects. Starting from the consolidated CE model, the paper describes how the application of intelligent assets, Internet-of-Things and big data, could be the basis to create a more promising circular model, where CE principles are extended to the entire product life-cycle, from product design to product utilization, considering also production assets and business strategies. Some case studies, described in literature, are presented to demonstrate how smart assets can interact with circular economy to create a new and more productive model of CE, characterized by a complete and effective circular platform for materials, products, assets and processes, where information and indicators are collected to measure circular efficiency.

Keywords: Circular economy, Fourth Industrial Revolution, Business model

1. Introduction

"In a circular economy, the value of products and materials is maintained for as long as possible. Waste and resource use are minimised, and when a product reaches the end of its life, it is used again to create further value" (European Commission 2015). The Circular Economy (CE) is recognized as an economy that is restorative and regenerative by design and aims to keep materials, components and products at their highest utility and value. It represents a systemic transition that can build long-term resilience, generates business and economic opportunities and provides environmental and societal benefits. Since the early 2000s, efforts to enhance industrial sustainability have focused on shift from a linear production to loop-closing strategies. However, the implementation of such sustainable industrial model is not straightforward and there is a huge gap between the big concept of CE and the practical actions (Homrich et al. 2018, Fellner et al. 2017, Ritzen and Sandstrom 2017). The concept recognises the importance of the economy needing to work effectively at all scales – for large and small businesses, for organisations and individuals, globally and locally. Many studies have proposed different concepts and models addressing the 3Rs (recycle, reduce and reuse), but such approaches are most applied to either single companies or single supply chain systems, because of directly supply chain relationship.

The main barriers to implementing the CE can be divided in 3 typologies (Korhoner et al. 2018). Technical barriers are related to inappropriate technology; lag between design and diffusion; lack of technical support and training and limited dissemination of innovation across both emerging economies and developed countries. Economic, financial and market barriers refer to high up-front and transaction costs; complex international supply chains; asymmetric information; resource-intensive infrastructure lock-in; failures in company cooperation and uncertain return and profit. Finally, there are institutional, regulatory, social and cultural limits due to misaligned incentives, lacking of conducive legal system, poor institutional framework, rigidity of consumer behaviour and business routines. These issues prevent the optimization of opportunities for sustainability enhancement. Suitable information and dedicated technology support are fundamental resources for sustainable organisations and decision-making processes. In fact, the lack of feedback information limits the development of performance models and the definition of infrastructure to keep materials in circulation. Data discrepancies, gaps and confidentiality issues hamper the measurement of circularity and the application of the CE models to a cross-industry network. A proper information flow throughout the supply chain enables companies and all the stakeholders to share and develop sustainability capabilities and build competitive advantages (Shi et al. 2017, Reuter 2016). The emerging technologies in the Fourth Industrial Revolution context can contribute to the procurement of the missing information and, consequently, can drive the diffusion of CE strategies and the definition of new products and business models based on CE concepts. In fact, in Industry 4.0 context, intelligent products, assets, processes and services are able to communicate and cooperate with each other and with people through the availability of some tools, such as Internet of Things (IoT), Big Data, data analytics and cyber-physical systems (CPSs). These smart technologies offer a variety of opportunities to unlock new sources of value creation for both individuals and companies (Jabbour et al., The Ellen MacArthur Foundation Report 2016). Embedded information technologies allow the ability to monitor and manage every physical object, collecting a great quantity of data. The massive, dynamic, continuous collection of data from installed emerging technologies are processed and analysed to make decisions in a cyclical way. Having a greater visibility, a more efficient data utilization and a tighter integration of underlying systems makes it possible a more reliable decision-making process to optimise the performance of systems and processes, save time for people and businesses, increase both workforce flexibility and product quality (Fiorini and Jabbour 2017). The main characteristics of collected data are the so-called 4Vs (Jagadish, 2015): a) volume, the great quantity of generated data; b) variety regarding measured parameters, trends and formats; c) velocity of data acquisition and analysis to object traceability; d) veracity about data quality and accuracy.

Intelligent assets can profoundly change every business environment, including CE models (Nobre and Tavares 2017, Accenture report 2015). In fact, the integration of emerging technologies is recognized as an effective tool to unlocking the circular economy potential. In particular, intelligent assets can provide 3 key types of information about resources (The Ellen MacArthur Foundation Report 2016): (i) location for real-time tracking; (ii) condition – technical or biological parameters (temperature, moisture…) or performance; (iii) availability – ownership, usage, demand. Recent research studies have demonstrated that knowing location, condition and availability of resources allows the achieving of the key CE drivers (extending the use cycle length of an asset, increasing resource utilisation, looping or cascading resources through additional use cycles and the regeneration of natural capital) through the definition of new business models, which exploit supply chain digitalisation. Nevertheless, the previous studies just explain the framework of new business models, identifying the gaps regarding in the integration between CE concepts and intelligent assets and giving some suggestions and propositions to their application, but do not provide applied real case studies (Jabbour et al., Tseng et al. 2018, Zhong and Pearce 2018).

In this paper, the gap between theoretical definition of new CE business models integrated with intelligent assets and their application in the industrial sector is overcome. In particular, the paper aims to define a new framework of a circular business model enhanced by the digital transformation, which characterized the Fourth Industrial Revolution. The structure consists of some underlying business models, which, thanks to intelligent asset integration, further strengthen the loop-closing strategies and create a more promising and productive CE business model. The proposed new model is demonstrated by some real case studies, which show how the application of the emerging technologies in the Fourth Industrial Revolution context can enhanced and extend CE principles, involving the entire product life-cycle, from product design to product utilization, considering also production assets and business strategies. So, thanks to the Fourth Industrial Revolution, the circular economy can be taken as an innovative business model that goes beyond the concept of sustainability.

2. A new circular business model enhanced by intelligent assets

The consolidated CE model is based on the application of direct strategies to increase the use of renewable and recycled resources to reduce both raw materials and process waste (The Ellen MacArthur Foundation Report 2015). Figure 1 shows the classic approach of CE strategy: compared to the traditional linear economy structure ('take-make-use-dispose'), CE aims to recapture value of post-production and post-consumption resources, products and packaging, realizing circularity through closed-loop production and consumption system, where a great part of waste is not disposed, but it is re-inserted in the same cycle.

Figure 1: the classic consolidated CE model: it aims to close the loop, involving all business operations, from design to material recycle.

CE model involves all the business functions to redefine products and service. It starts from a design revision and considers also processes, logistics, use and collection at the product end-of-life, in order to maintain resources in the loop, minimising residual waste.

The integration of the emerging digital technologies within the CE model provides companies with the opportunity to shift to a new, more productive and sustainable circular business model. Firstly, compared to the traditional and consolidated CE framework, the new circular structure is characterized by a further reduction of raw materials and energy consumption (Figure 2). Through the integration of different kind of sensors, every type of resource communicates upgraded data about its quantity, quality and utilization factor. IoT, a key enabler of digitalization, creates a network of connected objects and machine-to-machine communication interfaces, which feed cloud-based, big data analytics platforms. In this way, the availability of data about raw material condition, combined with new levels of control and automation in industrial and distribution operation, determines an increasing of plant flexibility and productivity, with the resulting reduction of raw material use and energy consumption. Increased efficiency in the use of materials brings other benefits: reduced process redundancy; minimisation of by-products and wastage; reduced error rates and maintenance costs due to the continuous monitoring of asset performance and energy consumption; high customisable, on-demand manufacturing; reduced air emissions due to the increased energy, material and logistics efficiency (CEPI report 2015).

The second difference between the consolidated and the new proposed CE business model is a further reduction of residual waste (Figure 2). The network between products, machines, logistics throughout the entire supply chain allows the continuous traceability of materials, in terms of location, condition and availability. In particular, data about material location make it possible the continuous monitoring of its movements, and, at the end-of-life, waste collection is optimized. The condition of resources is related to their behaviour due to usage and age. It is useful to define solution for material reuse, recycle or recovery. Moreover, waste can be monitored also in disposal. Finally, the determination of components and materials and their related typology, status and quantity represent the availability, which quantifies the rate of waste sorting, reuse and recycle. It provides maximum transparency for reverse logistics and material separation activities. Collecting data from waste gives also an insight of what consumers (industry and citizens) use. By the analysis of the waste flow, not just in quantities, rates, deposition times or collection prediction but also in quality, it is possible to determine what resources will be needed for humans (ISWA report 2017).

A further substantial change of the proposed model is the inclusion of maintenance in the cycle, not as underlying strategy during asset use, but as a specific phase of the life-cycle. Maintenance has a fundamental role above all during production operations. Good maintenance strategies and interventions preserve safety, product quality and avoid production delays, losses and unexpected shut-downs. By definition, maintenance drives one of the key aspects of the CE, that is the optimization/extension of products and equipment life. In fact, in the consolidated CE model, a proper maintenance acts during the use phase to repair products and equipment and to restore their initial conditions. Keeping components for a longer time means reducing the needs of new resources for new product production. Moreover, monitoring the condition of an asset and its performance and degradation trends, due to wear and damages during its use, can be the basis for decision-making about the replacement or the refurbishment of old and unsustainable products with innovative and more effective models (Chilamkurti et al. 2014). Nevertheless, maintenance can be exploited not only to refurbish equipment functions, but it can be applied also after product use at the end of its life. Maintaining a failed/refused asset allows the regeneration of the entire product or of their components, which can be reinserted in the cycle, upstream of the use phase, becoming regenerated new products for different users or supply chains. Figure 2 shows the proposed CE model, which presents i) reduced initial raw materials and final residual waste flows and ii) maintenance as a further operation in the closed-loop, after use.

Figure 2: proposed new CE business model, enhanced by supply chain digitalisation: it is characterized by a reduction of raw materials and energy consumption, minimization of residual waste and the presence of the new step "maintenance" that is inserted in the new enhanced cycle of CE model.

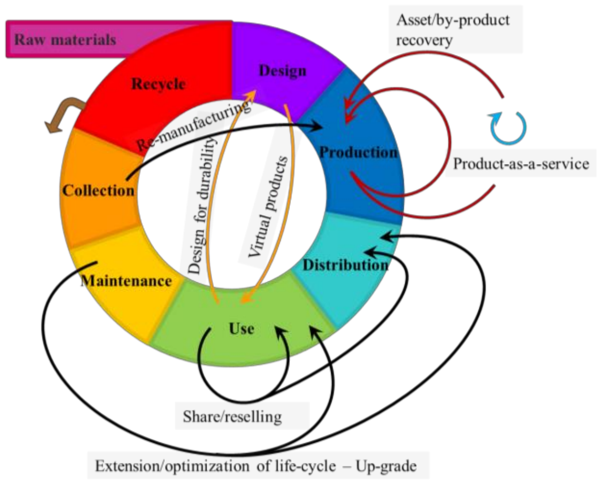

Figure 3: framework of the new CE business model enhanced by intelligent assets, emerging in the Fourth Industrial Revolution context. The model is characterized by a reduction of raw materials and residual waste and it considers also maintenance as a circular function. In this model some underlying options can be defined: a) resource recovery (purple cycles); b) product-as-a-service (light blue cycles); c) exchange (orange cycles) and extension of product life-cycle (black cycles).

Within this model, it is possible to define underlying business models, which create other cycles in the main defined closed-loop. Figure 3 identifies the circular underlying strategies, which can be obtained with the integration of intelligent assets (Accenture report 2014).

Asset/by-products recovery (red lines in Figure 3) – It consists of the recovery of useful resources, by-products or energy, which are typically discarded from industrial processes. The recovery of resources to feed into another process promotes return chains and transforms waste into value through innovative recycling and upcycling services. This business model leverages new technologies and capabilities to: (i) optimize process efficiency; (ii) recover materials at a level of value equivalent to the initial investment for raw materials. Recovered resources can be re-processed into new.

Product-as-a-service (light blue lines in Figure 3) – This model provides an alternative to the traditional model 'buy and own'. The products access is offered as service and components are used by one or any customers through a pay-for-use arrangement. It increases the productivity and the utilization factor of products. With this strategy, product longevity, reusability and sharing become sources of revenues and reduced costs.

Exchange (orange lines in Figure 3) – It consists of the replacement of old materials, products and technologies with innovative, renewable and sustainable ones. The exchange model involves both the design for durability and the exploitation of virtual products, in order to avoid unnecessary raw material use.

Extension of product life-cycle (black lines in Figure 3) – In this underlying business model, product life extension, sharing and reselling platforms and re-manufacturing are involved. Product life extension is obtained by asset repairing or upgrading. The value, typically lost through wasted materials, is maintained, recovered and improved. In this way, products stay economically useful for a longer time and can be upgraded, replaced only old components instead of the entire products. Sharing and reselling platforms promote collaboration among end-users (individuals or organizations). The result is a reduction of overcapacity and underutilization and the increase of productivity and user value.

The described underlying business models are possible solutions for companies for adopting CE. These models are not completely new, but many of the strategies would not be possible (or their potential would not be totally exploited) without the support of the emerging digital technologies.

3. Exploitation of the new enhanced CE model as circularity measurement tool

The CE represents a real opportunity for Companies, providing environmental, social and economic benefits. At now, it is typical that CE strategies within a Company are applied only to few business functions, thanks to some direct relationships with other partners in the same supply chain. The proposed framework of the new enhanced CE business model could be used as a tool for Companies to compare their actual business model and measure their circularity. In order to evaluate firm circularity, a questionnaire was developed and submitted to several Italian Companies (with different sizes and typologies), to collect and analyse data about the circular level of their products, processes and business models. The aim is to identify, for each interviewed Company, what are the transiting business functions to CE and what are the critical issues which limit the transition of other functions. These data will be combined to evaluate the circularity at different levels. In fact, the transition to a CE model can involve: (i) the entire Company, (ii) the entire supply chain; (iii) the entire industrial sector and (iv) the entire area, where the Company works. The final result will be the identification of the already available networks of circular Companies and, on the other hand, the risky situations. Data analysis is under development and the results will be showed in a further paper. The integration of innovative assets and the impending digital transformation in the context of the Fourth Industrial Revolution give the opportunity to overcome these critical aspects and to further develop other circular activities, extending their adoption at all the different levels.

4. Real case studies about the new enhanced CE business model

In this paper, cases studies are collected to demonstrate how emerging digital technologies can unlock the potential of circular economy. In particular, some case studies are reported for every previously described underlying characteristics which make the proposed CE model different from the consolidated CE concepts.

4.1 Reduction of raw materials: papermaking 4.0 example

Papermaking is a complex operation, due to the numerous processes and their integration with one another. Papermaking management is often characterized by an incomplete vision of the current situation, since data, such as laboratory test results, are not available or shared. This results in: low operating efficiency, underperforming and unstable production, high raw materials and energy costs and constant maintenance need. Voith, a global technology group involved in systems, products, services and digital applications in the markets of energy, oil&gas, paper, raw materials and transport&automotive, has developed a digital cockpit, designed to visualise complex processes and support efficient decisions with the final objective to increase process efficiency. Figure 4 shows a qualitative example of the structure of Voith system in a papermaking company. This system consists of a platform which continuously collects individual data from sensors, chemical analysers, machine and quality control systems and laboratory. The software allows the visualisation and the control of plant activities in a cockpit. Data are analysed to define when service actions are necessary.

The information is elaborated to produce a comprehensive overview of process and suggest options for further operations. In particular, the cockpit allows (Voith report 2014):

– the real-time visualization of the process situation (the preceding and upcoming four hours);

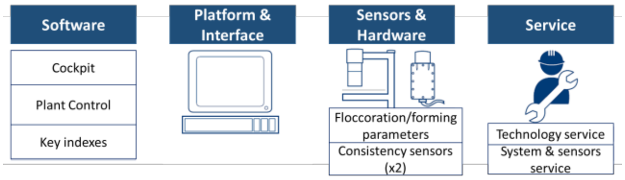

Figure 4: example scope of supply Voith system for papermaking application (Voith report 2014).

- a well-structured and complete selection of parameters according to technological relevance;
- the definition of key indexes for evaluating the efficiency of individual processes;
- a real-time prediction of offline measurements such as laboratory test results;
- the visualisation of the ideal process path and of historical trend analysis throughout long periods.

In paper industry, fluctuations in stock quality and white water recirculation processes disturb the delicate balance and necessitate manual interventions in the stock feeding and dewatering mechanisms. Having a cockpit on which visualising the entire process allow the stabilization and the coordination of dewatering, retention and flocculation activities. The resulting improved consistency in the process instantly saves raw materials, chemicals and energy and reduces the variation in quality values. This is achieved through a combination of sensors for analysing the processes, software for the real-time prediction of laboratory test results and control modules for the data sheet. The results are:

- greater material efficiency (increasing up to 2.5%);
- fewer fluctuations in paper quality (formation, porosity and opacity);
- efficient use of retention agents;
- energy savings up to 35% (drives, stock and vacuum pumps);
- reduced wear on forming wire;
- and reduced usage of raw materials (fibres, starch) for reaching paper strength targets.

4.2 Reduction of residual waste: improved waste collection and sorting solutions

The introduction of sensors and robots is expected to revolutionise waste sorting and recycling. Numerous smart bins are already on the market: Big Belly, Enevo, SmartBin are examples of technological solutions equipped with intelligent assets, which transmit information about filling level in order to optimize waste collection and truck paths (Hong et al. 2014).

In waste management, AMP Robotics has developed the robot Clarke, able to recognize and sort food and beverage containers through artificial intelligence. Using an advanced visioning system and deep-learning capabilities, it can spot milk, juice, and food cartons and pull them out, to divert them away from the landfill and sent instead to the appropriate recycling facility. Clarke picks up recyclable waste with 90% accuracy and is about 50% faster than a human, determining also a 50% reduction in sorting costs (Digital trends 2017).

4.3 Asset recovery: IBM reuse optimization tool

IBM is the global greatest IT and consulting service company. IBM has recently developed a reuse optimization tool to support industrial managers to improve products, components and materials reuse (The Ellen MacArthur report 2016). The IT tool integrates and analyses data about material and product technical features, condition, component availability and accessibility and market trends to be able to effectively know the real potential value of reuse of a product, component or materials. The information is elaborated to optimize resource management; increase resource productivity, reduce inventory and maximize company revenue. The Reuse Selection Tool enables individual businesses to build a business case for looping and cascading assets into further use cycles and potentially diverting them from landfill.

4.4 Tires-as-a-service – Michelin case studies

Michelin is one of the three largest manufacturers of the tires worldwide. Michelin has created an innovative program in which fleet customers do not purchase tires but rent them and pay per miles driven. Customers do not own the tires, but maintenance is always guaranteed, also in case of damages. This strategy could be implemented with a further service developed by Michelin. It is the EFFIFUEL system (Figure 5), a smart device which collect data about fuel consumption, tire pressure, temperature, vehicle speed and location (Technology and Operation Management 2016).

Figure 5: EFFIFUEL system developed by Michelin. It monitors some vehicle and tire parameters related to their condition, such as speed, temperature, pressure.

By the integration of the 2 services, the company can have numerous benefits. In fact, when used tires return among the manufacturer, the company receives useful information about: how recovery, reuse and recycle material (new tires or something completely different); quality of selected materials and the possibility to develop longer lasting tires.

4.5 Service handbooks based on augmented reality

Service handbooks are technical publications, which contain useful information and drawings to assist operators during asset maintenance. Traditional paper handbooks are surely economic and easy-making, but, on the other hand, their consulting is slow and their comprehension can be difficult. Augmented reality is an emerging technology, consisting of an interactive live view, where the physical environment are modified with the real-time addition of virtual contents. Maintenance handbooks are a developing application of augmented reality. Videos, documents, safety indications, drawings can be consulted thought smartphone, tablet or wearable devices (Palmarini et al. 2018).

The authors developed a maintenance handbook based on augmented reality for automatic packaging machines, produced by an Italian Company. Through wearable devices, the operators receive information about maintenance activities to conduct on machine when a failure occurs.

Figure 6 shows the visualisation through wearable devices which indicates the maintenance operations to be conducted on an automatic packaging machine to restore its initial performance.

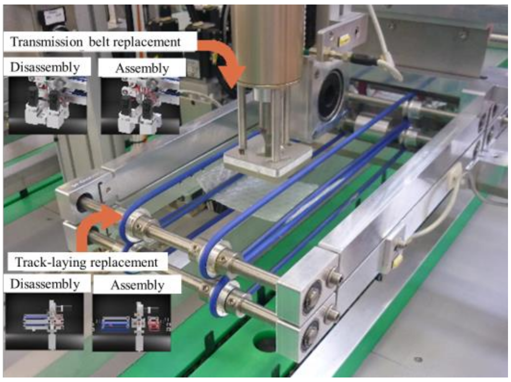

Figure 6: visualisation through wearable devices of maintenance actions for restoring of an automatic packaging machines. Videos and virtual documents and instructions were elaborated by the authors.

The adoption of augmented reality handbook produces mutual advantages for both customer and produced. The customer immediately visualizes indications to solve the problem. Restoring the anomaly, also the machine performance is re-established avoiding material wastage or defective goods. Moreover, the consulting and maintenance actions are simpler. Consequently, the operator itself can extend asset life-cycle. On the other hand, the producer guarantees an improved post-selling service, reduces materials and time to product traditional handbooks and creates a virtual document easy to modify.

4.6 Condition-based maintenance of submersible well pumps

Submersible well pumps are difficult to maintain since they are not visible and accessible, and maintenance intervention is expensive. Typical maintenance strategies in groundwater plants are (Bianchini et al. 2018):

- breakdown maintenance: it generated a low level of service, great extraordinary maintenance costs and non-optimized urgent interventions;
- preventive maintenance: it determines a partial exploitation of the entire product-life and it do not completely eliminate unexpected failures and down-time.

In both strategies, when a pump is replaced, no information about condition and availability are collected. Moreover, typically, the pump is entirely substituted and not only the failed components.

A more sustainable approach is condition-based maintenance (CBM). It consists of the continuous monitoring of the pump condition through the application of a sensor (e.g. vibration accelerometer). Monitoring the real-time status of the pump, maintenance interventions can be scheduled in advice and then carried out just before failure. In this way, the entire life of pump is exploited, guaranteeing a maximum level of service with reduced maintenance costs. Moreover, with a proper sensor selection, it is also possible to identify the cause of damage, replacing only faulty components. Otherwise, the faulty pump can be refurbished and reused in other processes. In all the described case the life of the pump is extended. Figure 7 shows the installation of a vibration sensor on a submersible well pump in order to conduct CMB with the final aim to exploit and extend the entire pump life-cycle.

Figure 7: vibration accelerometer installation on a 45 kW submersible well pump in a Publiacqua groundwater plant (Florence – Italy). The vibration of the pump is continuously monitored by the Department of Industrial Engineering of the University of Bologna, with the final aim to perform CBM strategy.

5. Conclusion

The paper illustrates a new business model based on CE principles. Compared to the consolidated CE strategy, the proposed model is enhanced by the integration of intelligent assets, emerging in the Fourth Industrial Revolution. The model is further demonstrated through the presentation of some real case studies.

The new enhanced business model highlights that the unlocking and the further implementation of CE strategies involve the entire supply chain, from suppliers to end-users. This need requires the fundamental support of innovative technologies in order to share information among the stakeholders.

The transition to a digital supply chain is unavoidable. Companies can only be divided into low or fast in relation to their adaptation degree. Consequently, companies should consider the Fourth Industrial Revolution as a big opportunity to revise their business model, shifting to a more circular one, which will deeply modify the entire global economy, but surely will bring environmental, social and economic benefits.

References

Accenture report (2014). Circular Advantage – Innovative Business Models and Technologies to Create Value in a World without Limits to Growth.

Accenture report (2015). Smart Production – Finding a way forward: how manufacturers can make the most of the Industrial Internet of Things.

Bianchini, A., Rossi, J. and Antipodi, L. (2018). A procedure for condition-based maintenance and diagnostics of submersible well pumps through vibration monitoring. *International Journal of System Assurance Engineering and Management*, 1-15. Article in press.

CEPI – Sitra – StepChange report (2015). Paper Industry 4.0. What digital can do for the paper industry.

Chilamkurti, N., Torabi, T. and Elhdad, R. (2014). Ontology-based framework for maintenance activity analysis. *International Journal Systems Assurance Engineering Management*, 5(1), 84-98.

Digital trends (2014). A recycling robot named Clarke could be the key to reducing waste.

European Commission (2015). Closing the loop - An EU action plan for the Circular Economy.

Fellner, J., Lederer, J., Scharff, C. and Laner, D. (2017). Present Potentials and Limitations of a Circular Economy with Respect to Primary Raw Material Demand. *Journal of Industrial Ecology*, 21(3), 494-496.

Fiorini, P. and Jabbour, C.J.C. (2017). Information systems and sustainable supply chain management towards a more sustainable society: where we are and where we are going. *International Journal of Information Management*, 37 (4), 241–249.

Homrich, A.S., Galvao, G., Abadia, L.G. and Carvalho, M.M. (2018). The circular economy umbrella: Trends and gaps on integrating pathways. *Journal of Cleaner Production*, 175, 525-543.

ISWA report (2017). The impact of the 4th Industrial Revolution on the Waste Management Sector.

Hong, I., Sunghoi, P., Beomseok, L., Jaekeun L., Daebeom J., and Sehyun P. (2014). IoT-Based Smart Garbage System for Efficient Food Waste Management. *The Scientific World Journal*, 1-13.

Jabbour, C.J.C., Jabbour, A.B.L.S., Sarkis, J. and Filho, M.C. Unlocking the circular economy through new business models based on large-scale data: An integrative framework and research agenda. *Technological Forecasting & Social Change*. Article in press.

Jagadish, H.V. (2015). Big data and science: myths and reality. Big Data Resource, 2(2), 49–52.

Korhoner, J., Honkasalo, A. and Seppala, J. (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics*, 143, 37-46.

Nobre, G.C., and Tavares, E. (2017). Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study. *Scientometrics*, 111, 463-492.

Palmarini, R., Erkoyuncu, J.A., Roy, R., Torabmostaedi, H. (2018). A systematic review of augmented reality applications in maintenance. *Robotics and Computer–Integrated Manufacturing*, 49, 215-228.

Reuter, M.A. (2016). Digitalizing the Circular Economy. *Metallurgical And Materials Transactions B*, 47B, 3194-3220.

Ritzen, S. and Sandstrom, G.O. (2017). Barriers to the Circular Economy – integration of perspectives and domains. *Procedia CIRP*, 64, 7-12.

Shi, L., Wu, K.J., Tseng, M.L. (2017). Improving corporate sustainable development: using an interdependence hierarchical model. *Resources, Conservation and Recycling*, 119, 24–35.

Technology and Operation Management (2016). Michelin: Tires-as-a-Service.

The Ellen MacArthur Foundation Report (2016). Intelligent Assets: Unlocking The Circular Economy Potential.

The Ellen MacArthur Foundation Report (2016). Intelligent Assets: Unlocking The Circular Economy Potential. Appendix: selected case studies.

The Ellen MacArthur Foundation Report (2015). Growth Within: A Circular Economy Vision For A Competitive Europe.

Tseng, M.L., Tan, R.R., Chiu, A.S.F., Chien, C.F. and Kuo, T.C. (2018). Circular economy meets industry 4.0: Can big data drive industrial symbiosis?. *Resources, Conservation & Recycling*, 131, 146-147.

Voith report (2014). OnEfficiency - Always keeping on track!

Zhong, S. and Pearce, J.M. (2018). Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing. *Resources, Conservation & Recycling*, 128, 48-58.