

## Article

# Circular Economy Model Enhanced by Intelligent Assets from Industry 4.0: The Proposition of an Innovative Tool to Analyze Case Studies

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**Abstract:** Although the circular economy (CE) is recognized as a source of value creation, there is a huge gap between the vast concept of CE and its practical applications. Particularly, the lack of information and performance indicators, in terms of economic, environmental and social aspects, does not allow for the assessment of the level of circularity of the products, processes or companies. Further development of other circular activities can be limited for this reason. In addition, intelligent assets arising with the digital transformation within the “Fourth Industrial Revolution (I4.0)” can support CE to provide these lacking aspects. Thus, the objective of this paper is to highlight how and how much the circular business models are enhanced by intelligent assets from I4.0, considering several case studies found in the literature, and through the application of an assessment tool with secondary data from the selected case studies. According to the tool, the CE principles are extended to the entire product lifecycle, from product design to product utilization, within the transition to novel business strategies. Two of the considered case studies are represented in the assessment tool, as examples, to demonstrate how intelligent assets can support circular economy in the design, assessment and comparison of circular initiatives. The visualization of existing innovative business models based on CE and enhanced by intelligent assets allows for the complete and effective evaluation of materials, products, assets and processes, due to the fact that information and indicators can be collected to measure and monitor circular efficiency.

**Keywords:** business model; circular economy; fourth industrial revolution (Industry 4.0); intelligent assets

## 1. Introduction

Since the early 2000s, efforts to enhance industrial sustainability have focused on a shift from a linear production to a circular economy (CE). CE is a growing topic, especially in the European Union, promoting the responsible and cyclical use of resources, possibly contributing to sustainability, as well as promoting innovative business models [1]. The shift to a CE represents a systemic transition that can build long-term resilience, generate business and economic opportunities, and provide environmental and societal benefits.

In countries such as China, Japan, the United States of America, as well as countries in the European Union, CE is already part of discussions with managers from public and private organizations, researchers, and legislators, related to the need for changes in the production and consumption patterns aimed at environmental protection and resources for future generations [2–5]. However, the implementation of circular business models is not straightforward and there is a huge gap between the vast concept of CE and its practical applications [6–8].

The main barriers to implementing CE were pointed out by [7,9]. The main issues highlighted prevent the optimization of opportunities for sustainability enhancement, and all can be reconducted to one main barrier: the lack of a proper information flow. Suitable information and dedicated technology support are fundamental resources for sustainable organizations, providing support to managers in decision-making processes. They allow the development of performance models and for infrastructure to keep materials in circulation. Data discrepancies, gaps and lack of trust about confidentiality are issues that hamper the identification and implementation of CE models and the measurement of circularity [10,11].

The emerging technologies in the Fourth Industrial Revolution (also called Industry 4.0—I4.0) context can contribute to the acquisition of the missing information and, consequently, can drive the diffusion of strategies, new products and business models based on CE concepts, through the opportunity to measure benefits and risks and can compare different circular solutions. I4.0 includes several technologies and associated patterns. Some studies on this topic have been conducted, such as on radio frequency identification—RFID and sensors [12], smart shop floor artifacts, smart factory (4.0) and multi-agent oriented digital factory [13]. Internet of Things—IoT [14], Big Data [15], 3D printing [16], and others [17] proposed a roadmap to the excellence of operations for sustainable reverse supply chain/logistics by implementing principles of Industry 4.0, and ReSOLVE model, through simulation. The authors of [18] propose a roadmap to boost the CE through I4.0 approaches. In [19], an IoT-enabled decision support to be used in circular business models (CBMs) is proposed.

However, there is no consensus about the categorization of technologies under the I4.0 umbrella, considering the opinions of several experts [20]. Additionally, numerous studies in literature showed that I4.0 can bring disruptive changes to supply chains, and that these can unlock the potential of circular business models and business processes [18]. Some of them show how the implementation of intelligent assets allows the achievement of a higher level of operational efficiency, productivity, and competitiveness [21,22]. Actually, it is impossible to conduct the transition to CE without thinking with regard to the intelligent assets included in the I4.0 umbrella [20].

Nevertheless, despite the vast scientific advancement in CE, especially in recent years, further theoretical and scientific deepening are needed [9,23]. It can be stated, specially for studies covering the topic of CE [24] found through a systematic literature review in the Science Direct, Scopus and Web of Science bases, considering 1195 papers published on CE, from 2008 to 2018, that the majority of them (864 papers/65%) used the descriptive case study as their strategy of research. Studies using the literature review were 4%, for surveys also 4%, scenario analysis 1.6% and, quantitative studies 1.6%, followed by simulation with just 0.66%.

Considering the above-mentioned, there are some research questions (RQ) which are exploited in our study:

RQ1: How can intelligent assets be part of conceptual models related to CE in the I4.0 context?

RQ2: How can the quantitative data be incorporated in conceptual models related to CE?

RQ3: Is the use of intelligent assets in conceptual models related to CE sustainable?

In this paper, some case studies, available in academic and grey literature, have been considered to highlight the benefits of the integration of digital technologies in the business model transition towards CE. The intention to cite these case studies is twofold: (i) to demonstrate some cases of circular business models using intelligent assets, and (ii) to collect some available secondary data (obtained from the case studies), used as input to provide examples of the application of the new visualization tools to assess CE, proposed by [25], demonstrating the benefits and the sustainability of the innovative CBM.

Starting from these valuable and implemented circular initiatives, the aim of this paper is to highlight the necessity to quantify them. Thus, the paper aims to demonstrate how and how much the CBMs are enhanced by intelligent assets from I4.0, through the application of an assessment tool [25], as the basis for creating a more promising circular model.

The proposed new method is illustrated by the analysis of two selected case studies, which show how the application of the emerging technologies from the I4.0 can enhance and extend CE principles.

The paper is structured as follows: Section 1 presents the contextualization, research questions and objective. Section 2 presents the theoretical background, exposing the main concepts covered in the paper: circular economy; circular business models, and digitalization through intelligent assets in the I4.0 context. Section 3 describes the main methodological procedures. In Section 4, the qualitative analysis of case studies is presented, categorized in: Manufacturing, Distribution and Use, Maintenance, and Waste Management, answering to RQ1. Section 5 presents examples of the use of the new visualization tool to assess the CBMs proposed by [25], to assess the benefits of the implementation of intelligent assets in I4.0 in CBMs and the discussion of the results in light of related theory. This will allow an answer to RQ2 and RQ3. Finally, Section 6 presents the concluding remarks, limitations of our study and suggestions for further studies.

## 2. Theoretical Background

### 2.1. Circular Economy

The life cycle of a good or service, represented by the stages of the production and marketing process, from the extraction of raw materials to the final disposal of waste, was commonly known by the expression “cradle to grave”, in which the cradle is the environment from which natural resources are extracted from and the grave is the environment as well, with the role of being the final destination of waste. Some other concepts were proposed by academics to change the understanding of the waste and reframe it as resource.

CE concept has origins in different schools of thought, such as ecological economy, general systems theory, industrial ecology, regenerative design, performance economy, cradle to cradle, biomimicry, cleaner production and blue economy [23,26,27].

A CE concept that considers the definition of sustainable development from the World Commission on Environment and Development was proposed [23]. The following was posed: “Is an economy built from social production-consumption systems that maximizes service produced from the linear flow of nature, society, and energy flow. This is done using flows of cyclic materials, renewable energy sources, and cascade-type energy flows. The successful circular economy contributes to all three dimensions of sustainable development. Circular economy limits the flow of production to a level that nature tolerates and uses ecosystem cycles in economic cycles, respecting their natural rates of reproduction” [23], (pp. 38–39).

The main aim of CE is described considering economic prosperity, followed by environmental quality, however, its impact on social equity and future generations is barely mentioned [28]. Additionally, [20] pointed out that CE should have two levels of analysis: (i) themes encompassed by norms, values, worldviews, concepts such as: organizational culture, learning, responsibility, or worldviews, and visions to contribute to the culture of the shared economy; (ii) themes involving measures, indicators, metrics, tools and instruments, such as practical and concrete physical flows of materials and energy, are important, and furthermore with consideration to, for example, fuel, energy and resources, inputs, waste and emissions, as well as physical flows between the nature and systems of production and consumption of society.

### 2.2. Circular Business Models (CBM)

Designing circular business models (CBMs) has been highlighted as an important enabler in the transition towards CE and stimulating and fostering its implementation on a micro-level is required [27–29]. The inadequacy of the traditional business models towards CE was pointed out by [27], p. 228. “A Circular Economy understanding lacking business models is one with no driver at the steering wheel”.

Although there are many case studies describing several types of circular business actions in the last decade, as surveyed by [24], there are very few studies that approach how a circular business model framework should look, besides that, these models are limited [29]. Furthermore, [28] found that,

despite some authors stating that novel business models are CE's main enabler, very few definitions explicitly refer to business models themselves.

In [30], it was proposed that eight sub-domains of research related to business models, which are definitions, components, taxonomies, conceptual models, design methods and tools, adoption factors, evaluation models, and change methodologies. The categorization of the existing body of literature on circular economy according to the components proposed by [29] identified how the CE principles can be applied to each component of the business model framework. The integration of CE business models with large-scale data through ReSOLVE, in the context of the I4.0 model, was proposed by [15]. Similarly, [18] proposed a roadmap to enhance the application of CE principles, considering an I4.0 context and technologies, through the ReSOLVE framework. In addition, [19] proposed an IoT-enabled decision support system to be considered in CBMs and showed how to use real-time monitoring of product lifecycle using I4.0 technologies, specifically, IoT and 5G.

It is possible to verify, analyzing these studies, that although some frameworks and CBMs were proposed in the literature, as well as some of them proposing the integration of frameworks and tools related to I4.0, none assess the CBMs by an I4.0 perspective with quantitative data, indicating the indicators to assess the circularity. Additionally, few of them included the social dimension of sustainability, as preconized by [8,23]. The environmental and economic aspects are better exploited, and the social and ethical practices related to it are not measured [8,23,28]. There are still few studies approaching the social dimension and most have a qualitative approach [28].

The discussion of these papers reinforces the research gap related to the lack of frameworks fed by performance indicators covering the three dimensions of sustainability (economic, environmental and social) with a holistic approach, which does not allow the assessment of the level of circularity of the products, processes or companies. Moreover, the need for a comprehensive conceptual framework for the circular business model in order to aid decision makers towards the transition of linear to circular economy was emphasized as very important by some authors, such as [29,31,32]. The consideration of intelligent assets is important, in the context of I4.0, to gather data related to the wide concept of sustainability and assess the circularity of the products, processes or companies. Moreover, an organization committed to driving their products and processes towards CE cannot avoid considering I4.0 technologies in its supply chain [20].

### *2.3. Digitalization through Intelligent Assets from I4.0 in Sustainable or Circular Business Models*

The technologies and systems arisen in Industry 4.0 (I4.0) will be instrumental for the development of the circular business models, as they enable better monitoring of product lifecycle and consumption [33,34]. As previously stated, some studies on this topic have been conducted in recent years and deserve to be considered.

In [12], the authors summarize the state of the state-of-the-art related to the effects of IT in the sustainable supply chain management, reviewing 55 peer-reviewed articles, published until May 2014. The results show deficits and lack of scientific discourse employing empirical techniques related to IT in sustainable business. The authors also identified six output/effects of IT: machine communication and multiagent; inputs and IT-supported processing; IT-enabled inter-organizational exchange; quantitative IT approaches and a sector focus. In [13], a study was conducted related to automated guided vehicles (AGV) in sustainable supply chain management, providing a conceptual tool of decision-making for facilitating the adoption of AGVs in industrial processes.

In [35], the authors conducted a systematic literature review to identify the I4.0 enablers of supply chain sustainability and found that the advances in technology created a greater demand for horizontal, vertical and end-to-end digital integration. The authors emphasized that I4.0 gets support, mainly from Cyber Physical Systems, Internet of Things and cloud computing, generating several benefits such as the establishment of smart production and production processes. Analyzing the integration of the circular economy and Big Data, under the ReSOLVE model from Ellen MacArthur Foundation [15], found that circular business models based on Big Data management should understand and observe

the need of key-stakeholders to be successful, mainly considering the complexity of the relationship between CE and Big Data.

In [17], the authors approached the operations for sustainable reverse supply chain/logistics by implementing principles of I4.0 and the ReSOLVE model, through simulation, and covered the information sharing in real-time mode, as well as the diffusion of green product in the market in the context of I4.0. The authors of [36] applied the decision method integrating Fuzzy Logic, Cumulative Prospect Theory and VIKOR based on the (partial) opinion of experts, in order to assess I4.0 technologies based on their sustainable performance and application. The rankings that were generated vary, considering the sector of application approached in the study, such as Automotive; Electronics, Food and Beverage; Textiles, Apparel, and Footwear. The authors found the following technologies, ranked from best to worst in an aggregated way (considering an average of the sectors): Additive Manufacturing; Artificial Intelligence; Augmented Reality; Autonomous Robots; Big Data and Analytics; Blockchain; Cloud; Cobot systems; Cybersecurity; Drones; Global Positioning System—GPS; Industrial Internet of Things; Mobile Technology; Nanotechnology; RFID; Sensors and Actuators, and Simulation.

These main technologies were corroborated in the study of [20], which found also that there is no consensus from experts related to the categories of technologies covered by the I4.0 umbrella. The authors carried out an extensive systematic literature review on the topic of circular economy, smart devices in I4.0 and found that there is no doubt that the exploitation of these technologies contributes to the adoption of the CE, and consequently, CBMs [20]. The authors also stated that it is impossible not to implement I4.0 smart devices when the company is committed to becoming more circular.

### 3. Methodological Procedures

As mentioned before, the intention to gather some case studies from literature aims to respond to the 3 RQs, particularly: (i) To demonstrate some cases of circular business models using intelligent assets (answer to RQ1); (ii) To obtain secondary quantitative data, deriving from I4.0 assets, to understand how they can support a further diffusion and development of CBMs (answer to RQ2); (iii) To assess the sustainability of the integration of I4.0 technologies in the CE context (answer to RQ3).

In the first part, the authors used the traditional or narrative literature review procedure. Compared to a systematic literature review, a narrative or traditional literature review aims to summarize the literature, although it does not make explicit to the reader the criteria used for the selection of sources and it is not exhaustive. The systematic review uses a well-defined approach to review the literature, which follows a protocol for selecting and analyzing sources. It is detailed and exhaustive, covering all the literature covered by the criteria defined in the protocol [37,38]. Considering the specific topic of this paper, focused on the 3 specific RQs, the authors think that a traditional/narrative literature review is suitable for the scope, since, due to the vastness and the variety of both CE and I4.0, which further increase when the 2 topics are integrated, a systematic review would require a dedicated analysis, based on specific scientific phases, such as planning protocol, operative research, classification and discussion, as applied in [39]. This is not the purpose of our study, which aims to just describe the use of intelligent assets in CBMs, and provide a tool to assess them, other existing case studies and future circular initiatives. Considering a traditional/narrative review, the authors gathered available research from Academic and Grey literature related to practices on circular economy and business models, trying to identify if the technologies and systems widely used in the I4.0 can enable the transition for circular models (RQ1). A deeper analysis of these case studies will allow us to understand if reliable, consistent and comparable data are already available to quantify the performance of CE models, mainly when they involve the intelligent assets (RQ2), and hence to verify the sustainability of these CBMs (RQ3).

To make clearer the criteria to select and filter the materials used, it is important to point out that (i) we considered papers published in last ten years; (ii) the scientific databases considered were Scopus, Web of Science, Science Direct, and also grey literature and documental research considered studies



from organizations that are very active about these topics, such as the Ellen MacArthur Foundation; European Commission; the International Solid Waste Association; beside the websites from some companies which provided statistics, projects and procedures related to a circular economy with the use of technologies; (iii) the keywords used to filter the materials were “circular economy” AND “business models” AND industry 4.0 OR digitalization OR intelligent assets; (iv) papers and materials describing case studies were considered as priority.

The theoretical assumption is that the transition to digitalization solves the problem of having available information, enhancing transparency, efficiency and convenience of a circular economy. The technologies and systems arisen in I4.0 will be instrumental for the development of the circular business models, as they enable a better monitoring of product lifecycle and consumption [30,31].

In the second part, the case studies provide examples and quantitative data to feed the conceptual circular model developed by [25] to illustrate the new visualization tool to assess the CBMs. This conceptual model aims to shift to a quantitative approach, which typically cannot be applied considering the unavailability and/or the diversity of data. Within this objective, the authors selected two case studies found in the literature to illustrate the use of the model and the data to be collected and inserted to assess the main impacts of the inclusion of intelligent assets in the transition to CBMs.

The data gathered from papers, reports and websites were analyzed through the technique of content analysis, proposed by [40], which is widely used in qualitative studies, to identify what elements have in common to group them into categories defined a priori and/or a posteriori. This technique of analysis is based on three stages: pre-analysis, exploration of the material and the treatment of the results. Thus, the cases were categorized into: (i) Manufacturing; (ii) Distribution and Use; (iii) Maintenance; (iv) Waste Management. In this study, the categories of analysis were defined “a posteriori”, and the studies dealing with aspects in common were aggregated.

Thus, the content analysis provided the elements to highlight the main technologies and systems used in the circular models by using the digitalization as core and the quantitative secondary data as input in the new visualization tool to assess CBMs. After the qualitative analysis of the studies, which is described in the Section 4, Section 5 presents an illustration of the model from [25], using some data from the two case studies, involving the industry of papermaking and tires. These two cases are very different from each other, but the authors will demonstrate that the visualization tool, proposed by [25], is flexible and that it can be adapted to each of the CBMs if proper data are available. Consequently, the two cases are provided as examples, but the tool can be used for other initiatives—both considered and not in this paper. However, it is important to emphasize that to show the full potential of the model, future applications should use empiric and primary data, obtained from organizations, processes or products that are facing the transition to CBMs through digitalization, and by using intelligent assets.

#### 4. Real Case Studies on Intelligent Assets as Part of CBMs—Qualitative Analysis

This section describes the qualitative analysis of some of the case studies selected and aims to answer the following research question:

RQ1: How can intelligent assets be part of conceptual models related to CE in the I4.0 context?

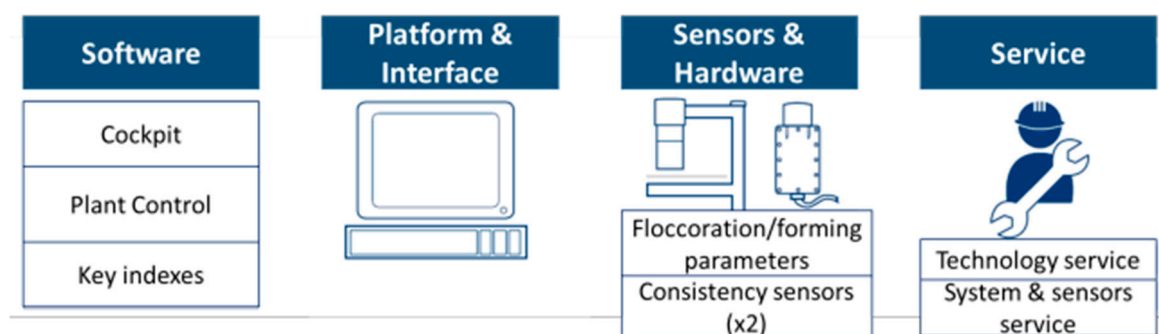
The case studies were categorized in every stage of the lifecycle: (i) Manufacturing; (ii) Distribution and Use; (iii) Maintenance; (iv) Waste management. It is important to remark that the literature research is intentionally not exhaustive, but the considered case studies can already respond to the RQ1.

##### 4.1. Manufacturing

###### 4.1.1. 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. These results are low operating efficiency; underperforming and unstable production; high raw materials; energy costs;

constant maintenance need. Voith, a global technology group involved in systems, products, services and digital applications in the markets of energy, oil and gas, paper, raw materials and transport and automotive, has developed a digital cockpit designed to visualize complex processes and support efficient decisions with the final objective to increase process efficiency. Figure 1 shows a qualitative example of the structure of the Voith system in a papermaking company. This system consists of a platform which continuously collects individual data from sensors, chemical analyzers, machine and quality control systems and the laboratory [41].



**Figure 1.** Example scope of the Voith system for papermaking application. Source: [35].

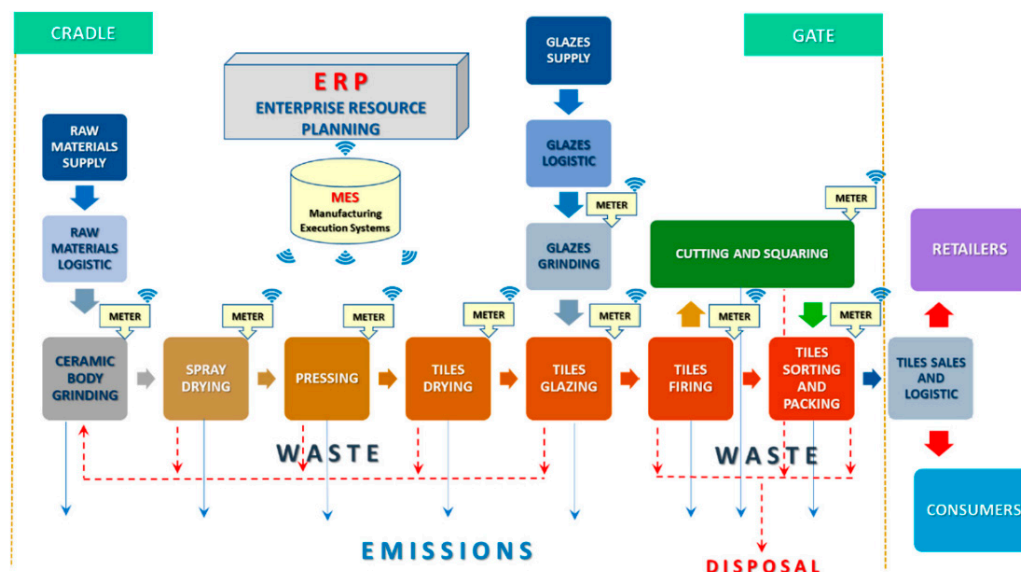
In the paper industry, fluctuations in stock quality and white-water recirculation processes disturb the delicate balance and necessitate manual interventions in stock feeding and dewatering mechanisms. Therefore, having a cockpit, in which visualizing the entire process allows for the stabilization and coordination of dewatering, retention and flocculation activities, can be of value. 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 analyzing the processes, software for the real-time prediction of laboratory test results and control modules for the data sheet. The results are:

1. Greater material efficiency (increasing up to 2.5%);
2. Fewer fluctuations in paper quality (formation, porosity and opacity);
3. Efficient use of retention agents;
4. Energy savings up to 35% (drives, stock and vacuum pumps);
5. Reduced wear on forming wire;
6. Reduced usage of raw materials (fibers, starch) for reaching paper strength targets.

#### 4.1.2. Digitalization of the Production Processes of the Industry 4.0 Environment in Ceramic Production Process

A new procedure was proposed, which was tested and validated in an Italian company producing ceramic tiles using digitalization of the production processes of the I4.0 environment, to implement the impact assessment tools (LCA—Life Cycle Assessment, LCC—Life Cycle Costing and S-LCA—Social Life Cycle Assessment) [41]. In addition, they used the business intelligence systems to provide appropriate sustainability performance indicators. The networks of sensors and meters within the Supervisory Control and Data Acquisition (SCADA) system already present in the company were used, which were connected by means of a Manufacturing Execution System (MES) via a Wi-Fi connection to the internal Enterprise Resource Planning (in particular, the ERP developed by the Company SAP) system. This analysis was carried out using the SimaPro 8.0.2 software and the IMPACT 2002+ evaluation method to quantify the environmental and socioeconomic impacts [42].

These sensors are intelligent and interconnected, able to collect some process data and communicate with each other without, however, giving significant information on production trends. Figure 2 shows the roadmap of the digitalization of the ceramic production process proposed.



**Figure 2.** The roadmap for the digitization of the ceramic production process. Source: [42].

As can be viewed in Figure 2, IoT technologies and I4.0 paradigm have provided support to collect, store and process all manufacturing data, overcoming the objective difficulties in managing data in this industrial system. ERP and business intelligence software were integrated with the environmental (LCA), economic (LCC) and social (S-LCA) impact assessment tools for the first technical analysis aimed at the subsequent strategic design oriented to the innovation of the business model towards sustainability [42].

#### 4.2. Distribution and Use

##### 4.2.1. Transformation of Forest-Based Bioeconomy into a Digital Platform Industry in UPM

A model explaining the co-evolution of the coupling of digitalization and bioeconomy of upstream and downstream operations and how it is transforming the forest-based bioeconomy into a digital platform industry was proposed by [16]. The study presented the reliability of the model through an empirical analysis focusing on the development trajectory of UPM (a forest-based ecosystem leader in Europe and a world pioneer in circular economy) over the last quarter century, highlighting its efforts towards planned obsolescence-driven circular economy. With the advancement of digital innovations, UPM has incorporated a self-propagating function that accelerates digital solution, which was triggered by coupling with a downstream leader, Amazon, in the United States.

UPM's resurgence can be attributed to its strategic shift towards a planned obsolescence-driven circular economy that is enabled by digital solutions integrating both upstream and downstream operations. It has taken strong initiative to shift from the fossil economy, which is not renewable by nature, towards a circular economy. This business model consists of five principles: (i) Circular Supplies, (ii) Resource Recovery, (iii) Product Life Extension, (iv) Sharing Platforms and (v) Products as a Service. These five principles can be satisfied by digital solutions [16].

UPM extensively use digital solutions in processes in the mills; however, in the future digitalization will increasingly be visible in customer-fronted processes such as sales, supply chain and quality monitoring. For instance, UPM launched an eOrder service for paper ordering in 2017. "The service developed for UPM ProFi, a biocomposite material for decking, helps in managing the certified installer base by combining online marketing and training, external services and customer relationship management platform" [16]. Another example is UPM Metsäni application, a mobile service for forest owners provides them volume, age structure and estimated value of the forest. The objective of this



application is to increase the wood trade by engaging the private forest owners. Figure 3 illustrates the coupling of the bioeconomy and digitalization.

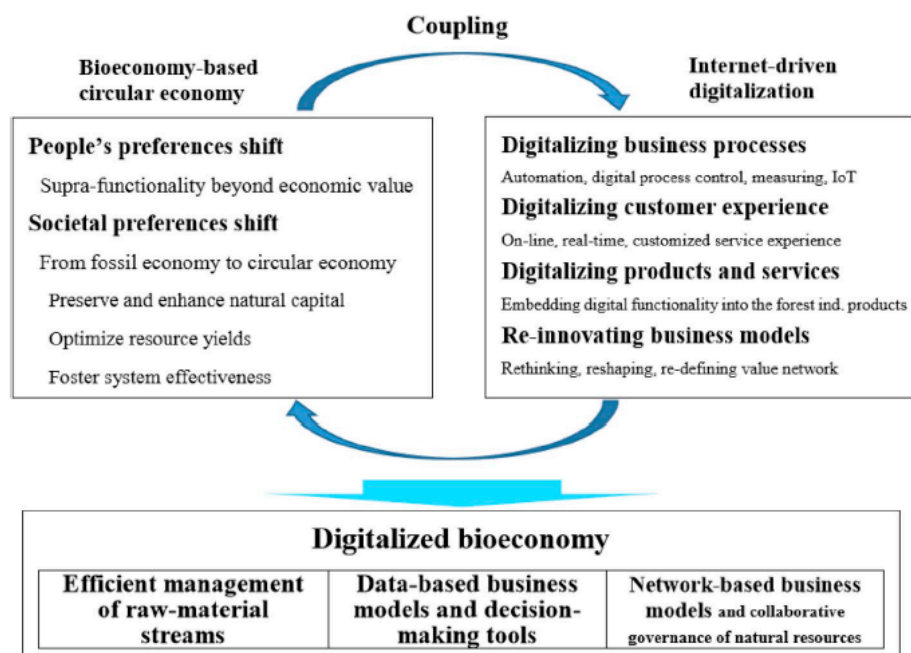


Figure 3. Coupling of the bioeconomy and digitalization. Source: [16].

A bioeconomy-based circular economy, which has formed the focus of UPM, is coupled with internet-driven digitalization which promotes the digitalization of business processes, customer experiences and products and services in addition to the re-innovating of business models.

UPM aimed to enhance its global market through a new B2B (Business to Business) eCommerce solution developed by Tieto, which is one of the largest IT services providers in Europe. The solution provided by Tieto is an eCommerce Cloud, covering the end-to-end service delivery, including design, development, and integration, which enables a greater flexibility and simplicity to UPM's operations. Tieto's eCommerce Cloud solution enables fast time-to-market, providing agility in development and adaptability for future business needs. Through Tieto, a virtual link has been established between the upstream leader UPM and the downstream leader Amazon. In addition, adopting a planned obsolescence strategy within a circular economy effectively uses the advancement of digital innovation led by the advancement of the internet to monitor the data related to the product [16]. Furthermore, because of constraints stemming from the reliability of data, particularly data on technological obsolescence and rate of depreciation of sold goods and services, successive monitoring and empirical surveys are strongly recommended [16]. A constraint of this issue is related to customers' agreement to allow us to gather this data.

#### 4.2.2. Tires-As-A-Service—Michelin Case Studies

Michelin is one of the three largest manufacturers of 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 in case of damage. This strategy could be implemented with a further service developed by Michelin. It is the EFFIFUEL system, a smart device which collects data about fuel consumption, tire pressure, temperature, vehicle speed and location [43].

Through the integration of the two services, the company can have numerous benefits. In fact, when used tires return among the manufacturer, the company receives useful information about

recovery, reuse and the recyclability of material (new tires or something completely different); quality of selected materials and the possibility to develop longer lasting tires.

#### 4.2.3. Smart Household Appliances: The Case of a Northern European Retailer

The case of household appliances of a retailer from a country in northern Europe can be denoted. This retailer provides washing machines, dishwashers, and tumble dryers, adopting a Product Service Systems (PSS) business model (BM). In addition to physically selling appliances, the company offers their customers the modality of subscriptions that give them the right of access to the appliance performance, for this purpose, retaining the ownership of appliances. This kind of model offers household appliances under a pay-per-use scheme, which may be classified as a use-oriented BM [43].

The company enables the circularity in its processes, through its PSS BM considering that: (i) Each subscription replaces the ownership of low-efficient appliances with high-efficient ones, thus reducing the use of consumables such as energy, water and detergents and therefore increasing resource efficiency; (ii) The replacement of the end-of-life concept, since each appliance is collected and renovated when the subscription ends [44].

In order to make this process feasible, the company supplies to households an IoT kit developed in-house which connects appliances to the internet through a plug-and-bridge instrument, transforming the appliances into smart and connected products. This change enables appliance monitoring and control during its usage, as well as the collection of large amounts of Big Data, which are properly analyzed through Analytics [44].

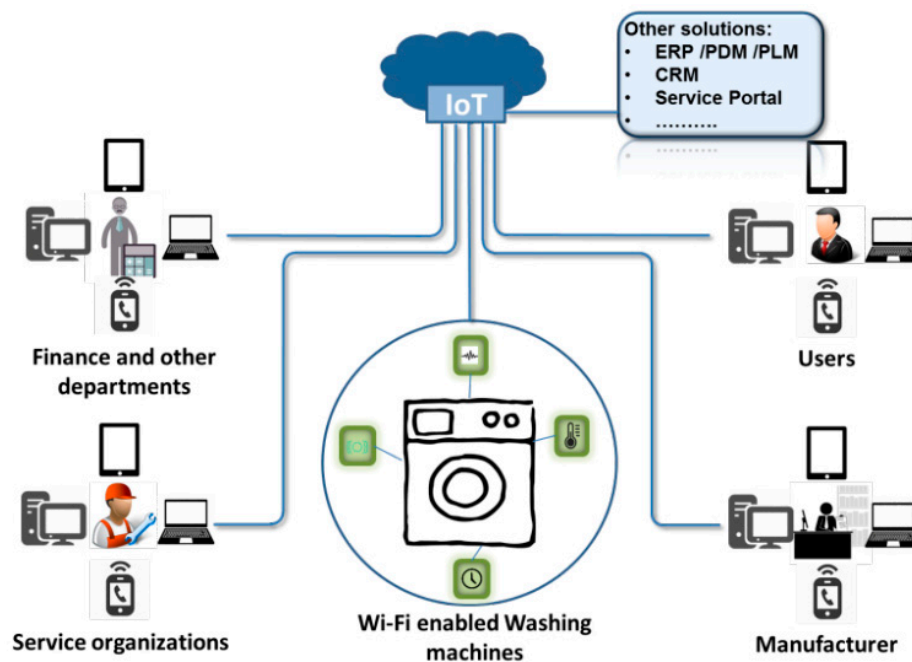
An important issue to be emphasized is that operational risks, usually generated by careless behavior in product usage, are mitigated thanks to the monitoring of users' activities through the IoT. By offering advanced services, such as the optimization of the usage phase and the provision of preventive and predictive maintenance, both included in the subscription fee, the company can face these risks. In fact, thanks to the analysis of Big Data collected through the IoT tool, Alpha discloses to customers personalized advice such as, in the case of washing machine subscription, the better washing cycle duration or the better washing temperature to reduce energy and water consumption. More specifically, a mobile App provides hints to use fewer detergents and to conserve water and energy, starting from the IoT monitoring of the electricity, water and detergent consumption, the washing load, the number of cycles, among others [44]. The connection with devices as cell phones, computers and clouds and others, allow the collection of data by the manufacturers and retailers.

#### 4.2.4. Smart Household Appliances: The Case of Gorenje Group

Gorenje Group is one of the leading European home appliance manufacturers, selling white goods and kitchen appliances together with services and spare parts. As a step towards a Circular Manufacturing System (CMS), the company aims to move from their traditional product sales model to service-based business models (SBBM), allowing users to subscribe for clean laundry services based on a pay-per-use schema, retaining the ownership of the machines, and the responsibility of service, maintenance and take-back. This is aligned with CMS because it allows customer satisfaction to be met and allows manufacturers to keep control over their products, throughout the product lifecycle.

A change in the business model requires that product design, supply chains and information management infrastructures are also changed accordingly to fit the new business model. This work mainly focuses on ICT (Information and Communication Technologies) infrastructure and partly covers the product design aspects that are necessary to consider to fit the business model shift [45].

This research is part of a project funded by the European Commission (EC) which aims to bring forward a commercial IT-platform integrated with the hardware and software through an Internet of Things (IoT) platform for information communication and sharing. Figure 4 shows an overview of ICT infrastructure.



**Figure 4.** Overview of ICT (Information and Communication Technologies) infrastructure. Source: [45].

This ICT infrastructure consists of machines that can sense different operational data using sensors and send the data to an internet server. The internet server, which also stores a set of digital twins of the washing machines, processes the data to detect anomalies. The information and data are then made accessible to different users through a web application [45].

Gorenje must develop new use cases beyond these essential features. The potential lies in improving after-sales services through predictive maintenance and by providing customized services, collecting usage data to optimize operations and utilization of machines with software updates. A well-recognized and popular IoT platform called Raspberry Pi (Rpi) is being used. Raspberry Pi is a credit card size microcomputer, with 1.2 GHz ARM microprocessor and integrated wireless card. Most importantly, it has 17 general-purpose input/output (GPIO) analog/digital channels and strong user-based support. The electronic parts of the washing machine are connected to Rpi through a motherboard developed especially for this purpose. Rpi typically comes with a Linux operating system, which automatically takes care of Wi-Fi connection and makes it easier to add as well as manage multiple sensors. The Rpi platform is useful for an easy and fast deployment of connectivity feature which also resembles electronic devices that are ready for production. In general, Rpi provides an easy and cheap way for testing new ideas [45]. The ICT system is responsible for managing:

1. Asset management: to be able to handle individual machines;
2. Machine cards: to keep track of the machines' real composition;
3. Integration to IoT platforms (ThingWorx in this case): to get real-time operational data and predictive maintenance notifications;
4. Integration to ticketing systems (Jira in this case): to handle the process for planning and processing the predictive maintenance;
5. Uploading of maintenance protocols: to document the predictive maintenance activities.

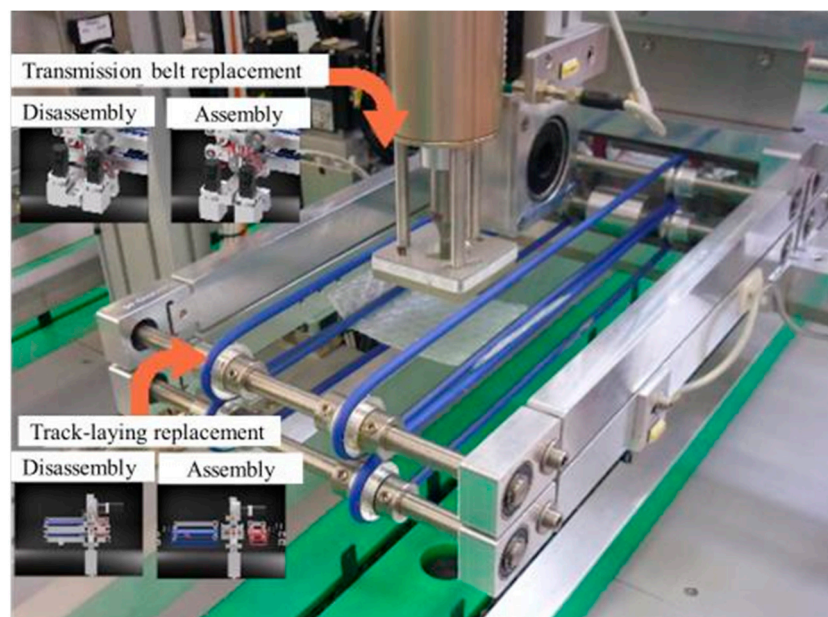
#### 4.3. Maintenance

##### 4.3.1. 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 to make, 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 is 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 through smartphone, tablet or wearable devices [46].

These 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 which maintenance activities to perform on the machine when a failure occurs. Figure 5 shows the visualization through wearable devices which indicates the maintenance operations to be performed on an automatic packaging machine to restore its initial performance.



**Figure 5.** Visualization through wearable devices of maintenance actions for restoring of an automatic packaging machine. Source: [47].

The adoption of augmented reality handbook produces mutual advantages for both the customer and producer. The customer immediately visualizes indications to solve the problem. Restoring the anomaly, also the machine's performance is re-established avoiding material wastage or defective goods. Moreover, the consulting and maintenance actions are simpler. Consequently, the operator itself can extend the asset lifecycle. On the other hand, the producer guarantees an improved post-selling service, reduces materials and time to produce traditional handbooks and creates a virtual document easy to modify [47].

#### 4.3.2. 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 [47]:

1. Breakdown maintenance: it generated a low level of service, great extraordinary maintenance costs and non-optimized urgent interventions;
2. Preventive maintenance: it determines a partial exploitation of the entire product-life and it does not eliminate unexpected failures and downtime.

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). By monitoring the real-time status of the pump, maintenance interventions can be scheduled in advance and then carried out just before failure. In this way, the entire life of the 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 cases the life of the pump is extended [47].

#### 4.4. Waste Management

##### 4.4.1. Reduction in Residual Waste: Improved Waste Collection and Sorting Solutions

The introduction of sensors and robots is expected to revolutionize 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 the filling level in order to optimize waste collection and truck paths [48].

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 send them 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 [49].

##### 4.4.2. The K-Project: Recycling and Recovery of Waste 4.0—“ReWaste4.0”

The project Recycling and Recovery of Waste 4.0—ReWaste4.0—as part of the Austrian COMET program is a long-term, innovative, and cooperative project on the highest scientific and technological level with distinct economic relevance. The waste management, new Industry 4.0 approaches (e.g., digital networking, communication between waste quality and plant performance, robotics, and other) are investigated and implemented in this project for the purpose of developing the waste management system towards a “circular economy” with specific focus on interconnected recycling and recovery processes of highest quality. The purpose of the ReWaste4.0 is to increase the sector specific know-how and strengthen the international technology leadership of Austrian enterprises [50].

In recent decades, waste management has evolved from a pure logistics industry to a manufacturing industry due to the ever-increasing volume of waste and the trend towards recycling. Nevertheless, logistics continues to be an important means of linking the waste management sector with the rest of the industry. Ongoing new technical possibilities through digitalization make it possible to optimally further develop logistics in waste management [50].

## 5. A Visualization Tool to Assess Sustainability of CBMs Enhanced by I4.0

### 5.1. A Tool to Integrate Quantitative Data from Intelligent Assets on CBMs

Based on the analysis of the available diagrams, their strengths and weaknesses, [25] proposes a new visualization tool, encompassing the transition to an enhanced and more sustainable business model based on CE concepts. The main purpose of the authors was to develop and provide an easy and intuitive tool, based on a graphical methodology. The authors assume that the model should be completed with systematized information, to take a snapshot of the actual situation and identify further steps. The model is presented in Figure 6.



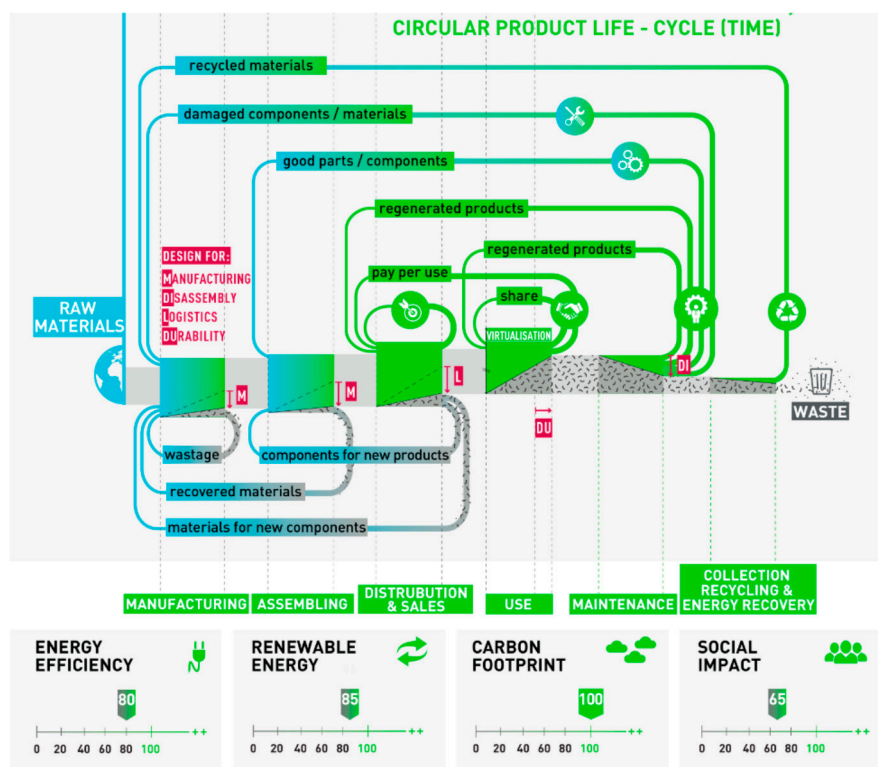


Figure 6. New circular business model visualization tool. Source: [25].

The main purposes of this new circular business model visualization tool are quantification of the potential of novel sustainable strategies; provision of visual information for the identification of novel synergies, barriers, necessary stakeholders and, provision of information in order to evaluate some indicators to assess and compare circular strategies. There are two main novelties of this tool. The first is the capability of quantifying the circularity of the designed and implemented initiatives. The missing opportunity to quantify, measure and hence compare circular initiatives surely limits the possibility to identify new ideas and implement circular activities. Companies usually use a great quantity of Key Performance Indicators (KPIs) and tools for the measurement of their operations, since the collected information helps the decision making. For a practical implementation of CE, the tool must provide the possibility to quantify the circularity grade of the initiatives. The second innovative feature of the tool is its capability of adaptation to every product and industrial sector. The tool must be easily adapted to every product and industrial sector, as will be demonstrated in this paper.

As mentioned by [25], this is a theoretical model that needs to be completed with systematized information, which can be surely provided by intelligent assets.

The next section has the purpose of presenting two case studies, as examples, in which the consideration of CE and environmental efficiency can be optimized with the use of intelligent assets.

## 5.2. Examples of the Adoption of the Visualization Tool to Quantify the Sustainability of CBMs Enhanced by Intelligent Assets

To illustrate the application and the usability of the tool proposed by [25] and assess circular initiatives, enhanced by intelligent assets, the authors selected two case studies from Section 4. The illustration of the model tries to answer the following research questions:

RQ2: How can the quantitative data be incorporated in conceptual models related to CE?

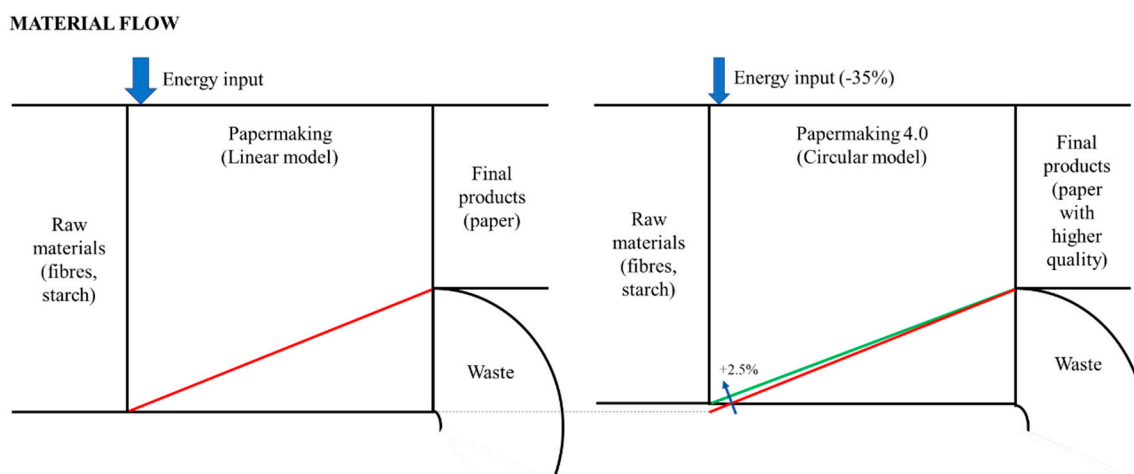
RQ3: Is the use of intelligent assets in conceptual models related to CE sustainable?

In particular, for the selected case studies, the visualization tool was set up to highlight the effects of the implementation of digital technologies on products, processes, companies and supply chains in the transition to a CE. These two cases are chosen since they are very different from each other,

but any other initiative could have been considered. However, as explained in the following section, since the adoption of the tool would be partial also for other studies, due to the lack of data, it is provided for only two cases. Nevertheless, the aim is to understand what data must be collected with intelligent assets to feed the tool and then quantify the sustainability of the implemented CBM, enhanced by I4.0. The assessment of circular initiatives with a standardized and systematized tool allows for the evaluation of impacts (environmental, economic and social) through specific KPIs and the comparison between different opportunities. The result of the assessment phase is the provision of reliable, consistent and comparable information that support the selection of the optimal solutions, the consideration of all barriers (technological and non-technological) and the identification of potential stakeholders to effectively close the loop.

#### 5.2.1. Visualization Tool Applied to Manufacturing—Reduction in Raw Materials in Papermaking 4.0

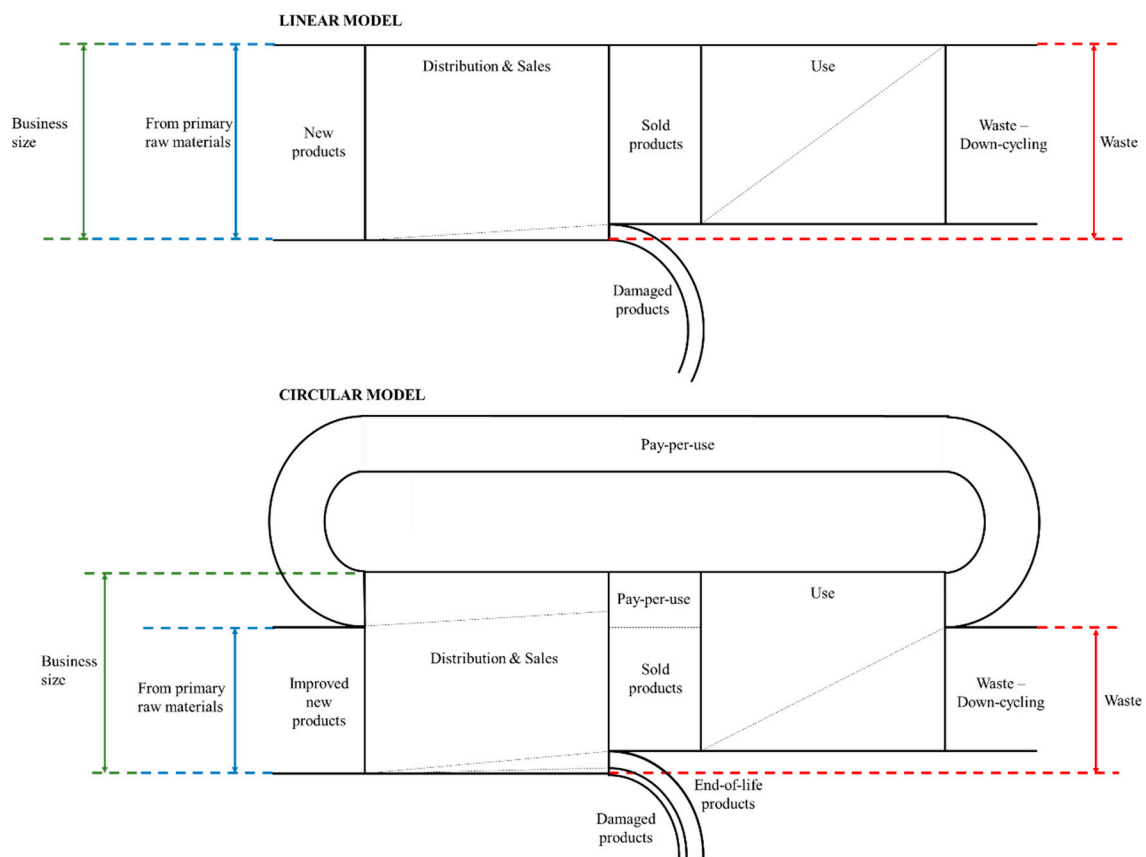
In the papermaking case study, the implementation of digital technologies improved the manufacturing process efficiency (+2.5%—data from [40]). This activity acts on the highest and most valuable level of the waste hierarchy, since it allowed us to reduce the use of raw materials and energy consumption in relation to the same quantity of manufactured final products, as shown in Figure 7. The insertion of all data will allow the measurement of raw material and energy intensity for the papermaking process before and after the implementation of digital technologies. This information will bring the evaluation of some environmental KPIs, such as process efficiency (ratio between final products and raw material input (%)) and energy efficiency (ratio between energy input and final products (kWh/ton)).



**Figure 7.** Set-up of the framework of the proposed visualization tool to assess the benefits derived from digital technologies in the Papermaking 4.0 case study. Quantitative data are provided by [41].

#### 5.2.2. Visualization Tool Applied to Distribution and Use—Tires-As-A-Service

The application of the visualization tool at the Michelin case study (tires-as-a-service) shows the main benefits derived from the transition from a linear model, based on the tire sales (upper part of Figure 8), to a circular business model, based on a pay-per-use model (lower part in Figure 8). In particular, maintaining the total amount of tires distributed to the final user, but considering that a part of this quantity is not sold but managed as a service, the immediate results are (i) a reduction in waste generation and (ii) a reduction in products derived from primary raw materials. Another consequence of the transition to this circular business model could be an increase in business size. It could look worse since the total distributed tires are the same but with increased inputs.



**Figure 8.** Set-up of the framework of the proposed visualization tool to assess the benefits derived from Michelin tires-as-a-service case study.

Nevertheless, it must be considered that the efforts (raw material costs, energy time, labor) required by the pay-per-use service are minor and the savings can be re-invested to: (i) increase product quality and extend its life; (ii) hire new personnel for the service; (iii) increase the business. To have a quantitative vision about this shift, it is necessary to introduce to the tool some data, such as the amount of tires with a pay-per-use arrangement in relation to the total tire distribution, the percentage of end-of-life tires, the efforts derived from the transition. With a proper information flow, also in this case, some KPIs can be calculated: an environmental one could be the Material Circularity Indicator (MCI), defined by [31], while the increase in the number of employees could be considered as a positive social impact, since it generates a direct benefit to the community in which the company is located, also increasing the income and the level of consumption and the generation of taxes to the government.

### 5.3. Discussion of Results in Light of Theory

In this paper, the intention is to address the following research questions:

RQ1: How can intelligent assets be part of conceptual models related to CE in the I4.0 context?

RQ2: How can the quantitative data be incorporated in conceptual models related to CE?

RQ3: Is the use of intelligent assets in conceptual models related to CE sustainable?

Related to the RQ1, the traditional/narrative literature review demonstrates that I4.0 can support the transition to a CE in each stage of the supply chain. It derives that due to its potentiality, the transition to a digital supply chain can be also a big opportunity for companies to revise their business model, shifting to a CE. Continuous and real-time data collection, elaboration, and information exchanges, generated by the I4.0 technologies, have the potential to effectively unlock CE concept implementation [15,44,51–53].

The inclusion of technologies allows the achievement of five major features of the Fourth Industrial Revolution, as demonstrated by the practical case studies described in Section 4 [16,41–45,47,49,50], digitalization; automation; human machine interaction; value-added services and businesses; automatic data exchange and communication. The integration of these characteristics in the physical world makes every asset (resource, product, machine or building) intelligent, providing the ability to learn, communicate and collaborate themselves with humans. It is the concept of interoperability, one of the main advantages that distinguishes the Fourth Industrial Revolution. Interoperability has been defined as the capability of two systems sharing data, information and knowledge and the ability to understand each other for improved functionalities [53]. In particular, these features provide three further benefits, compared to the traditional and consolidated CE framework.

1. Through the integration of different kinds of sensors and their insertion within a network of connected objects, every type of resource communicates upgraded data about its quantity, quality and utilization factor. In this way, the availability of data about raw material condition, combined with new levels of control and automation in industrial and distribution operations, determines an increase in plant flexibility and productivity, with the resulting reduction in raw material use and energy consumption [41]. Increased efficiency in the use of materials brings other benefits: (i) reduced process redundancy; (ii) minimization of by-products and wastage; (iii) reduced error rates; (iv) reduction in maintenance costs due to the continuous monitoring of asset performance and energy consumption; (v) high customizable, on-demand manufacturing; (vi) reduced air emissions due to the increased energy; (vii) material and logistics efficiency [54,55].
2. A second difference derived from the implementation of intelligent assets is a reduction in residual waste. 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 for the continuous monitoring of its movements, and, at the end- of-life, waste collection and reverse logistics are optimized. The condition of resources is related to their behavior due to usage and age. It is useful to define the 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 also gives 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 [56]. Consequently, digitalization and embedded information for waste can really increase the efficiency in waste management and hence in resource use [57]. Some studies cited previously, studied the use of intelligent assets in sustainable supply chains [18,20–22]; however, they did not show how to effectively integrate them in CBM models.
3. Finally, one of the key aspects of the CE, that is the optimization/extension of products and equipment life obtained with circular initiatives (such as pay-per-use and sharing platform) and a proper maintenance strategy, is further driven by the implementation of intelligent assets [16,43–45]. 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 [56].

The enhancement of CBMs by intelligent assets allows managers to choose their CE goals and choose the proper I4.0 technologies that best support their strategies. In fact, I4.0 technologies provide beneficial conditions to support circular strategies such as the re-design of products and processes, recovery and reuse of waste and sharing models [58]. Furthermore, by adopting the digital CBMs they

can identify the better set of I4.0 technologies supporting the transition towards the CE and assess its performance [20]. The transition to a digital industry is still in progress, but it is unavoidable and consequently depends only on the adaptation velocity of companies.

Regarding the RQ2, the unprecedented amount of information generated by embedded assets constitute a passport for materials and resources and enables a further exploitation of the classical circular model, but also the development of other CE initiatives, which can reduce the gap between theoretical definition of CE and its practical implementation. The lack of quantitative data has limited the implementation of CE strategies only in few business functions or with other partners in the same supply chain due to consolidated relationships. Their availability allows the identification of newly covered or unexplored opportunities, as demonstrated by the application of the proposed visualization tool [25], since the collected data make it possible for three main activities: (i) the quantification of the potential of new sustainable strategies; (ii) the identification in advance of the probable barriers; (iii) the provision of indications of suitable solutions to both implement these strategies and overcome the limitations. The result is a strong reduction in the risk of investment within the circular economy and its greater diffusion [53].

Considering the RQ3, we verified that although the transition under a new digital economy is associated, not only to natural resources and technologies, but also complex—considering future trajectories of societies—firms and individuals [16]; covering also the social aspects, the technology plays an essential role in this context. The evolution towards I4.0 consists of integrating new production technologies, to improve working conditions and increase productivity and quality, at the same time that reduces the negative environmental impact [42]. These production technologies can generate a synchronicity between the components of the production and logistics, such as the exchange of information between machinery and plants, automatic warehouses for feeding the production lines or storage of finished products and any other device that is part of the workflow of value creation, which can generate an innovation with the use of systems already implemented in the companies, such as ERP [42].

Thus, the three dimensions of sustainability can be reached using a CBM enhanced by intelligent assets. The economic investment returns in the medium and long term, reflected in savings in raw materials and resources such as energy, water and heat, reduction and reuse of waste, extension of the useful life of equipment and installations, greater productivity, reduction or elimination of penalties for generation of negative environmental impacts, and better working conditions. The environmental impacts are reflected in the efficiency of the use of resources (energy, water, heat and raw materials), in the reduction in waste, and consequently, in the reduction in the negative impact on the environment, through emissions, extraction of resources and extension of the life cycle of equipment and products. The social benefits and the social innovation related to the enhancement of CBM by intelligent assets lie on the better labor conditions and the respect of human rights. However, to effectively quantify the sustainability of new CBMs integrated with I4.0, data from intelligent assets must be available, consistent and comparable. The proposed visualization tool [25] provides a practical procedure to measure it, but the analysis is still partial since data are typically not available. It is mainly the case of social impacts; specifically, there is still a lack of quantitative data related to social aspects in the literature, and considering the available secondary data, it was not possible to exploit this dimension of sustainability in the new visualization tool proposed. As mentioned before, there is a lack of approach to social impact, and respective indicators, in the context of circular economy [8,23,28,41], mainly considering that the social aspects are essentially qualitative and subjective, which makes difficult its mensuration through numbers. An alternative was proposed [41] using the Social LCA to measure it, which transforms the qualitative information in scales. Thus, considering the lack of appropriate business models [31,32], and of those that do exist, limited transferability [29], a comprehensive conceptual framework for the circular business model in order to aid decision makers towards the transition of linear to circular economy is necessary. A framework enriched by the support of intelligent assets, such as IoT, Big Data and Analytics, ERP, RfID, sensors, among others, allows companies to



overcome the challenges related to financial and operational risks, loss of ownership, willingness to pay, cannibalization, technology improvement and uncertainties related to return flow of waste, which were pointed out by [44].

As pointed out by [44], these CE challenges can be overcome by the means of four digitally enabled functionalities: (i) monitoring users' activities; (ii) the provision of advanced services such as preventive and predictive maintenance or the optimization of the usage phase; (iii) digital upgrade; (iv) estimation of product and component residual life. A notable example is the new challenge that arises when products become smart, i.e., the challenge related to privacy and data security, because customers are reluctant to share with the provider the data that are required to perform preventive maintenance or the optimization of the usage phase, thus compromising their provision. In addition, it is required that the new business models based on circularity consider the innovative and collaborative efforts, involving multiple stakeholders, such as suppliers, customers, and producers [15].

For this purpose, the methodology proposed in this paper can aid SMEs (Small-Medium Enterprises) and big corporations, providing a tool to integrate timely and consistent data from I4.0 to support decision making about CE, ensuring the measurement of the CBM's sustainability. The CE represents a real opportunity for companies, providing environmental, social and economic benefits. As of now, it is typical that CE strategies within a company are applied only to few business functions, thanks to some of the direct relationships with other partners in the same supply chain.

Companies can implement the tool, fed by I4.0 data, to compare their actual business model and measure their circularity. The aim is to identify what the transiting business functions are to the CE and what the critical issues are that limit the transition of other functions. These data can also be combined to evaluate the circularity at different levels: (i) the entire company; (ii) the entire supply chain; (iii) the entire industrial sector; (iv) the entire area, where the company works. The result will be the identification of the already available networks of circular companies and, on the other hand, the risky situations.

The analysis of case studies presented in this paper can be complemented with empiric quantitative data in future studies. The integration of innovative assets and the impending digital transformation in the context of the Fourth Industrial Revolution provide the opportunity to overcome these critical aspects and to further develop other circular activities, extending their adoption at all the different levels.

## 6. Concluding Remarks

The novel, enhanced business models, proposed in this paper, highlight that the unlocking and the further implementation of CE strategies involve the entire supply chain, from suppliers to end-users. This demand requires the fundamental support of innovative technologies in order to share information among the stakeholders. The framework can aid decision makers providing useful and timely information in order to enable the transition towards a circular economy.

Some limitations of this paper should be pointed out. Considering that this study was based on secondary data, from the literature review, and documental analysis, it lacks in obtaining all necessary data to fully apply the assessment tool. For this purpose, we gathered some case studies from the literature in order to illustrate the use of the model, however, for testing its validity, it would be important to apply the model with the input empirical data that should be easy to collect through the shift to digitalization. Another limitation is related to the consumer perspective, which was not approached in this paper. The consideration of the traditional/narrative literature review to gather papers and other documents related to the case studies can be recognized as another limitation, considering that it did not exhaust the literature related to the use of intelligent assets in CBM in the context of I4.0. Finally, the inexistence of quantitative data on literature related to the social dimension of sustainability did not allow the full demonstration of the new visualization tool to assess the CBM enhanced by intelligent assets.

Further studies can, besides applying the model proposed in several industrial and commerce segments including the analysis of empirical data, cover the economic, environmental and social aspects,

providing a holistic approach aiding the decision-making. In addition, future studies can approach the perspective of consumers by including a customer relationship management platform in the model. This approach can overcome a constraint pointed out for some authors related to customers' agreement to allow the gathering of data through intelligent assets. Furthermore, the application of the model proposed allows the measurement of key performance indicators related to environmental, economic and social issues. We also suggest the use of systematic literature review procedures, with well-defined criteria and protocol to cover a wide range of the literature on the topic.

The main contribution of this paper lies in proposing a systematized framework that considers circular business models enhanced by intelligent assets, which allows the gathering of timely and consistent data, providing elements to more reliable decision making. 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.

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