New promises AI brings into circular economy accelerated product design: a review on supporting literature

Malahat Ghoreishi[1,*], and *Ari* Happonen[2]

[1]LUT University, School of Business and Management, 53850 Lappeenranta, Finland
[2]LUT University, School of Engineering Science, 53850 Lappeenranta, Finland

Abstract. Promoting and applying circular strategies in the product planning stage by industrial designers have significant environmental impacts. Product design has an enormous influence on sustainable ecology. Huge amounts of data analysis in designing circular products as well as reducing human biases in testing and prototyping are the main reasons for urging digital technologies in industries. Digitalization assets in ecodesign in collaboration with humans and as a complement for human skills. This study found the circular design tools and strategies which can help organizations in their product designs and the way artificial intelligence enhances product circularity. Real-time data transformation and analysis ability can help in massive data analysis which is less time consuming and less energy consumption is needed. In addition, rapid prototyping and fast testing will reduce the waste in design process. Furthermore, AI transfers precise data and information on materials and products' availability, condition, and accessibility which makes easy monitoring and enables remote maintenance as well as reuse, remanufacturing and repair opportunities.

1 Introduction

The Circular Economy (CE) approach has been significantly discussed on industrial development globally and has gained the attentions of industries, scholars and policy makers worldwide over the last decades. According to Ellen Macarthur Foundation [1], CE is a "system restorative and regenerative by design, which aims to maintain products, components and materials and their highest utility and value". Despite the outstanding benefits that CE brings to businesses, the transition from a linear economy, "make, use, dispose", towards a circular model requires huge efforts of governments and policy makers in cooperation with industries and end-users. However, Macarthur Foundation [2] argues that besides the numerous advantages of circular business models, which are considered as sustainable business models, renewing and restoring materials can be highly costly for industries. Hence, certain changes in business models are required for companies that can generate additional challenges. These things companies need to be able to tackle, include new operational needs in asset management, innovative approaches for supply chain novelty, logistics approaches reinvention for currently unfamiliar waste products as well as designing manufacturing services and enhancing quality control [3]. On the other hand, designing these aspects increases the complexity of the CE workflow; thus, product design development and related business model improvements are essential in accelerating the move towards circularity [4].

Since few changes can be made on the products once the resources, characteristics and specifications are allocated for designing a certain product, integrating circular strategies at the early stage of the product design process has a vital role in value creation as well as supply chain [5, 6]. Accordingly, companies need more innovative solutions on product design strategies of narrowing or closing the resource loops. Bressanelli et al. [7] discuss that the fourth industrial revolution (4IR) such as Big Data, Artificial Intelligence (AI) and Internet of Things (IoT) can pave the way to overcome the challenges towards circularity for industries. According to Ellen MacArthur Foundation [8], AI plays an important role and is a subset of the technologies that asset in enhancing product circulation as well as smart management and predictive maintenance. AI is discussed in this study as an accelerator in circular product design by data collection and analysis, fast testing and prototyping.

2 Background & research focus

2.1 Circular product design

In the world of CE, product circularity aims to maximize the value of components and materials of products during the longest time period. Product life extension which can be attained by repair, remanufacturing and refurbishment, is the central economic and social model [9]. Kraaijenhagen et al. [4], argues that in transition towards CE, the challenge is how to reduce natural resource utilization and working on promoting positive societal and

* Corresponding author: Malahat.Ghoreishi@lut.fi

environmental impacts by rethinking of the ways helping in maximizing the value in offered products. Therefore, product design strategies are essential in value creation along with "customer value proposition, supply chain, value networks of the companies and capturing the value of new offerings"[10].

2.2 Technologies in CE

According to recent research, digital technologies have an urgent role and increasing involvement to enhance CE solutions to overcome current challenges [7, 11]. Digital technologies contribute to product visibility through intelligent sensors and provide information on assets, location, condition and availability [12]. Currently, one of the most important roles of circular business models is to share and lease the products instead of selling [13, 14]. Waughray et al. [15] mention that digitalization is one of the key solutions in accelerating the move towards circularity. Moreover, utilizing digital technologies such as AI, IoT or Blockchain enhances the ways in developing and improving transparency and traceability throughout product lifetime [16]. In a digital world, producers have the opportunity to monitor, control, analyze and optimize products' performance through smart, connected products and to collect valuable data of the usage of materials, components and goods [17].

Correct use of those technologies can boost efficient reverse logistics & materials and goods considerations that then gain second life and also it accelerates the CE concept worldwide with the suitable recycling process, which uses limited resources [2]. But e.g. for efficient reverse logistics, talented and knowledgeable logistics operators will be needed. Operators who know how to position themselves correctly between manufacturers and subcontractors [18]. A combination of digitalization driven technologies and novel business models innovation may provide significant new opportunities towards more sustainability for industries in terms of value creation, value capturing and CE [19]. For example, by using digital design processes to build one of the configurable products [20], in a sustainable manner. Sitra [21] mentions that manufacturing industries can gain tangible benefits by a digital reinvention of the industry to move towards Circularity. However, some technologies are known to be prone to risks that must be considered and balanced with possible higher rewards and benefits these technologies offer compared to more traditional options. As an example, one way of doing this is to do feasibility analysis for the new technology [22] and compare it directly against know and well matured traditional (golden standard) solutions.

2.3 Artificial intelligence and CE

AI enables automatic and remote monitoring of the efficiency during the manufacturing process as well as the product's end lifecycle in CE. AI enhances massive data analysis which is generated over the manufacturing process, disposal or use [3]. According to Ellen MacArthur Foundation [8], Since AI has the ability to deal with complexity and can improve the huge amounts of data awareness, it is considered as a complement for human capabilities which helps in more efficient learning from feedbacks. Faster and rapid prototyping, learning process by repeated designing cycles and feedback collection are requirements in accelerating the transition of the complexity of redesigning key features to a better economic model. Accordingly, AI can play a significant part in enabling the systematic shift.

3 Literature review process and finding

According to European commission [23], all the products during their lifecycles have an impact on the environment in all the phases from the use of raw materials and natural resources, manufacturing, packaging, transport, disposal and recycling. The environmental impact of over 80% of the products is determined at the phase of design. According to [24], "circular product design: elevates design to a system level, strives to maintain product integrity; is about cycling at a different pace, explores new relationships and experiences with products, and is driven by different business models". Product design plays an essential role in CBM and affects the company's competitive advantage [25]. Van den Berg and Bakker [26] define five main characteristics of circular products from the inner loop to the outer loop as: Future proof, Disassembly, Maintenance, Remake and recycling (Fig. 1). In circular product design, products are designed to last and use longer (future proof), can be disassembled, maintained, remade (components) and recycled (materials).

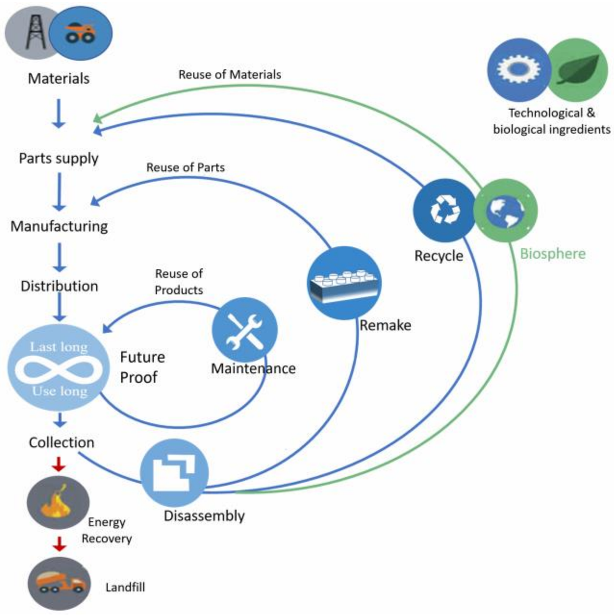

Fig. 1. Circular product design (adapted from Van den Berg and Bakker 2015)

According to these characteristics, Van den Berg and Bakker [26] introduced a guideline as a tool in product design process (Fig. 2) which can be used in discussion within a design team to define the aspects that requires consideration for CE and to realize on which area and what degree the product needs to be improved. As it was

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mentioned previously, the product designs can be seen as key factor already in early stages of product development processes for circularity. As such the designers of these products play an important role in developing changes to product for enhanced disposability and they can build improved relationships/bridges between end-users needs and the product to be designed [27]. The characteristics of the products in questions will have a defined and direct influence on the process of creating and the way it will be managed [28]. Basically it means that the design has a big and vital role when supply chain loops are considered to be closed up [29]. Additionally, proper supply chain partners and collaborative measures [30] will be needed to be able to run all these design actions effects efficiently through the supply chain.

3.1 Circular Design strategies

Vanegas et.al [23] define three product designs in the vision of CE: “increasing material efficiency, product life extension, improving recycling efficiency”. Bocken et.al [13] divided CE into three fundamental categories of narrowing, slowing and closing the resource loop (Fig. 3) in which, “narrowing” the loops is related to the resource efficiency, “slowing” the loops focus on designing the products with long lifetime whereas “closing” the loops focuses on materials and products recycling as well as system’s leakages removal [13, 31]. According to Atlason et.al [32], proper functionality of such strategies at the End-of-Life design is gained when producers’ and end-users’ intentions on handling the end-use of products are aligned. For example, if the consumer tends to repair or reuse the product after a useful lifetime, it is not desirable for the producer to design for better recyclability. Pocock et al. [33] mention that materials circulation through products lifetime extension generates revenue for the businesses. Essoussi and Linton [34], discuss that the willingness of users to purchase products with reused or recycled was related to the perceived functional risk of achievement paves the way towards implication of Industry 4.0 [35] products. Therefore, where the perceived risk is high, and the margin price is low, users like to buy new products. Moreover, users’ tolerance to uncertainty defines the willingness to pay for the perceived quality of the refurbished products [36]. According to [10], circular design options can develop downstream circularity, therefore they might be part of business model innovation.

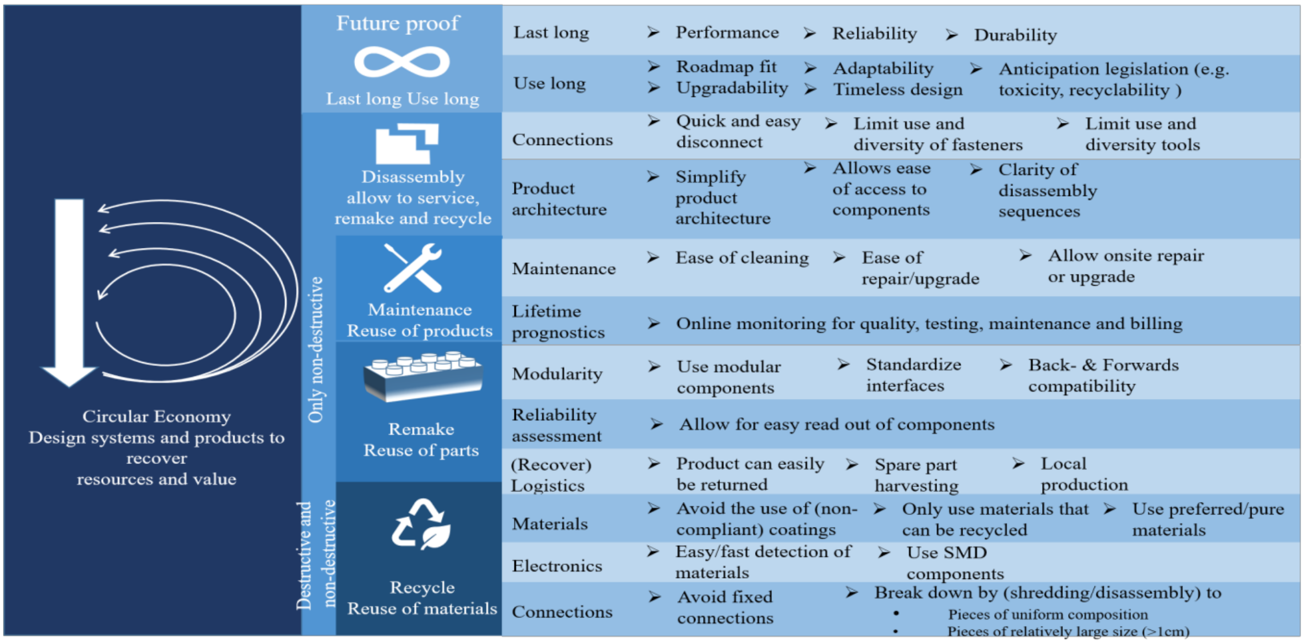

Fig. 2. Circular product design tool (adapted from Van den Berg and Bakker 2015)

3.2 Industry 4.0 and CE

Although circular strategies aim to close material flows and to extend the lifetime of the products, [37], companies face serious challenges in the transition towards a circular model. Challenges which prevent sustainability goal. Here, digitalization provides precise information such as location and availability of the products to help closing the material loops which facilitates companies in the transition towards a more circular sustainable model. [12]. Moreover, utilizing digital technologies leads to reduce waste, prolongs the life expectancy of the products and minimizes transaction costs which enable efficient processes in organizations [15]. Thus, it helps to enhance circular business models of closing/slowing and narrowing the loops by increasing resource efficiency [12].

According to [38, 39] the term Industry 4.0 (Table 1) is “a combination of AI, Cyber-physical systems (CPS), Internet of Things (IoT) and Industrial internet, in other words, internet services”. Industry 4.0 contributes to optimizing sustainable solutions to reducing emission from industrial systems via transforming and utilizing information generated from various smart devices [40].

While 4IR is not capable to overcome all the challenges towards circularity, such technologies offer more cost-efficient tools [41].

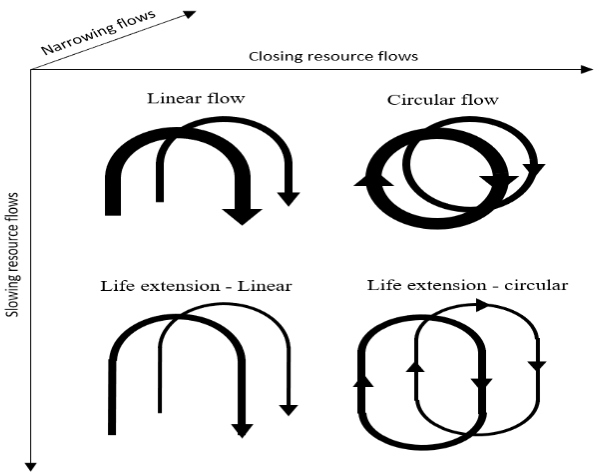

Fig. 3. Slowing, closing and narrowing the loops strategies (adapted from Bocken et al., 2016)

Integration of CE and Industry 4.0 leads towards new levels of sustainability, which can work as a motivation enabler for business organizations to move towards sustainable supply chains as well as a new outlook for production and consumption [35]. Industry 4.0, which is also known in the production industry context as smart manufacturing, helps managers in decision-making by providing real-time information on machines, flow of components and production, monitoring performance and tracking parts and products [42]. New Industry 4.0 based technologies are enablers that will pave the way in integrating CE principles through tracking products post-consumption and recovering components [43]. Fig. 4 illustrates 4IR solutions for circularity. CE business models could benefit by Industry 4.0 by applying these technologies in the form of sensors and apps; for example, to plan, monitor, predict and control the lifecycle of the products [15, 44]. Precise demand forecasts will make it easy to implement the CE principles, thus more precise plan to reuse and preparation of used materials can be made [45]. Moreover, digital technologies can help in product design and making decisions on production through sustainable operations management by providing data on the resources to reduce resource consumption, improving productivity and extending the lifecycle of products [7]. When we integrate products with sensors, we basically allow performance monitoring and as an example, this performance data could be used for predictive maintenance and future product maintenance related requirements specification purposes. Therefore, organizations can provide high-quality services to customers. Furthermore, these technologies enable connectivity and sharing information related to supply and demand; for example, by website and apps which connect people to organizations [43]. In addition, since such technologies could be used to collect the information on consumers' behavior, they could also help the organizations in improving the design of products and services for a better and more user-friendly equipment, that would then meet the customer's needs and satisfaction more completely [46]. With the ability to collect data from operations, processes and objects, digital technologies can help to identify possible failures that create waste and to prevent further failures [43]. In addition, referring to CE and sustainable manufacturing, improvement in using data, machinery, equipment and software can reduce the need for limited resources as well as the ecological footprint of the production is leading to new business models [45]. However, manufacturing industries would face challenges such as cybersecurity concerns, developing new talent, new business models and definition of the new strategy in attempting to implement Industry 4.0 [47]. A pioneering roadmap towards an Industry 4.0-based CE business is illustrated in Fig. 5.

Table 1. A framework of Industry 4.0 in Intelligent Manufacturing System (adapted from Zhong et al., 2017)

Design	Machine	Monitoring	Control	Scheduling
Smart design	Real-time control and monitoring	Real-time information sharing	Data-driven modeling	Marketing
Smart prototyping	Collaborative decision-making		Big data analytics	Warehouse management
Smart controller			Data-enabled prediction	Transports
Smart sensors				

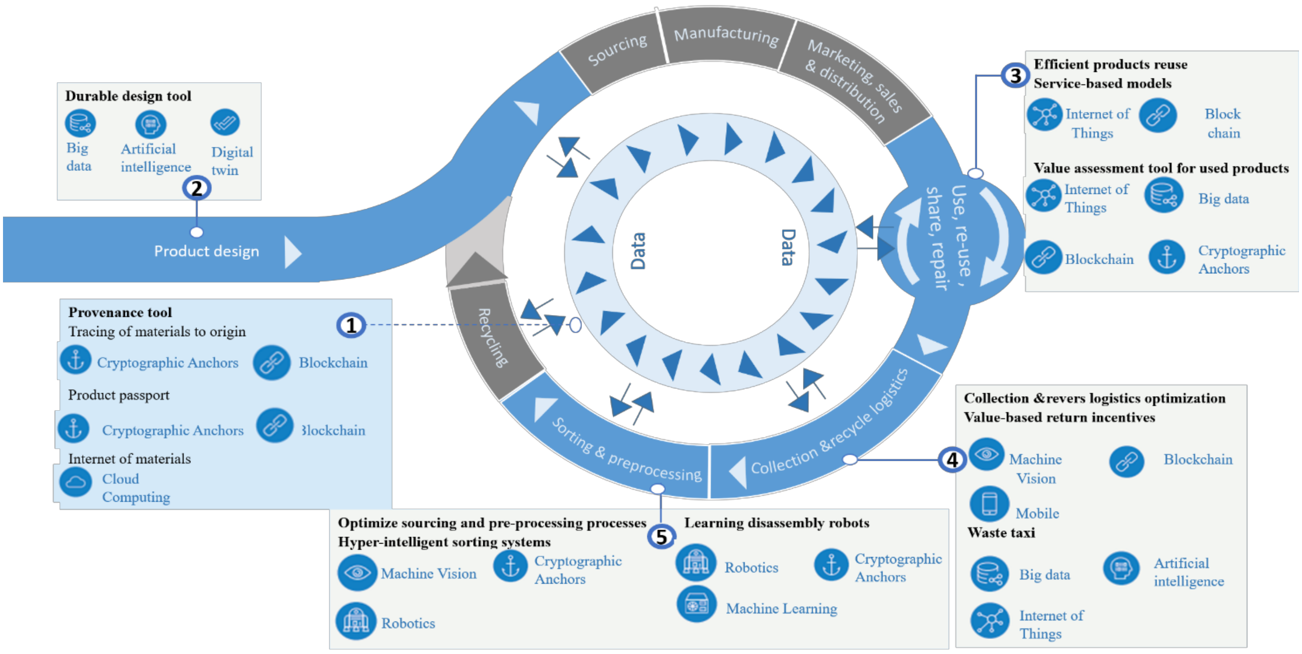

Fig. 4. Industry 4.0 solutions for circularity (adapted from World Economic Forum and Accentures Strategy, 2019)

3.3 Industrial AI

According to McCarthy [48], "Artificial intelligence is the science and engineering of making intelligent In the end short authors view how that might indicate a research gap and how on another hand the non-full SLR nature of literature review might need additional machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable.". According to Kaplan, in his book AI: What Everyone Needs to Know, AI relates to the computer programs which are capable to behave in such a way that if demonstrated by a human, it would be considered as intelligent [49]. Hence, the definition of AI concerns the comparison and alignment between human and machines. Lee et al [50] distinguish AI as "a cognitive science", which enhances research activities in the areas of natural language processing, machine learning, image processing, robotics etc. Brynjolfsson and Mcafee [51] mention that AI has huge advances in both areas of perception and cognition AI algorithms can be used in various functionalities such as pattern recognition, prediction, optimization & planning, and integrated solutions with robots. Fig. 6 presents the areas of AI development AI techniques in future states.

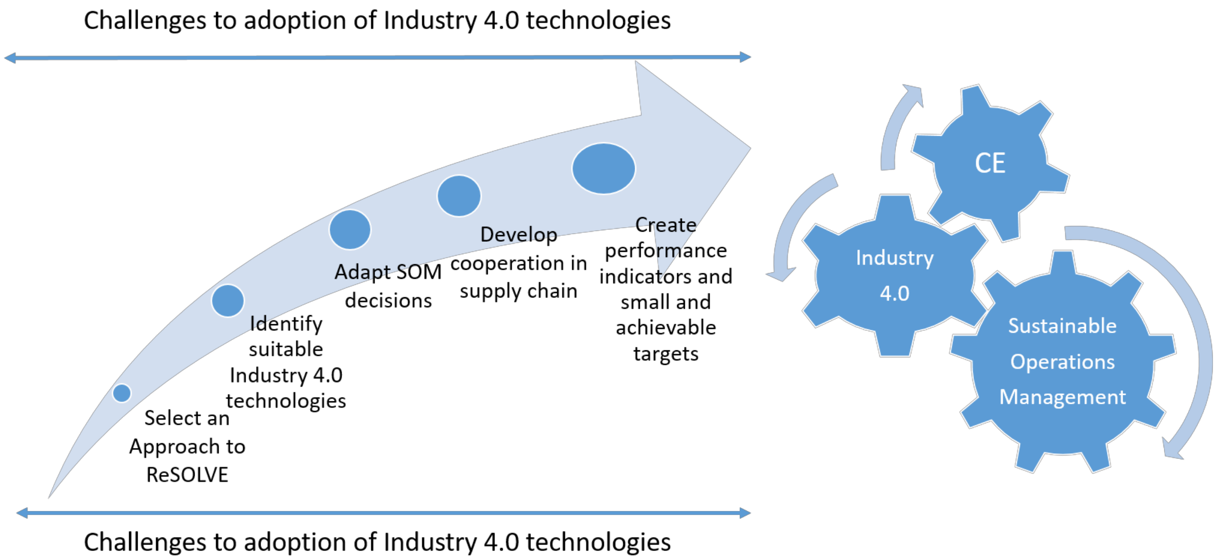

Fig. 5. Roadmap towards Industry4.0 and CE (adapted from Jabbour et al., 2018)

The progress of AI relates to the advancement in three enablers of real innovations: learning algorithms, computing power, and training data. Advanced robotics among many digital technologies progress in 4IR, has been identified as a significant alternative in the entire value chain. It is estimated that 1.8 million industrial robots will operate in the production system globally which represents an approximate market of $35billion worldwide [52]. According to research done by Jacoby and Paltsev [53], Artificial Intelligence is capable of reducing costs for business actions, based on its capability to predict future things, based on current knowledge. AI has the ability in data collection from the human on the information that they have and to generate novel information that didn't exist. Market competition and demands are the challenges that industries have faced during the past years worldwide and Industry 4.0 can bring a radically innovative solution in businesses. Machine learning along with AI techniques brings solutions in a systematic way and discipline for industrial applications [50]. The aim of Industrial AI is to validate, develop and deploy different machine learning algorithms with a sustainable performance for industrial applications.

3.4 Smart manufacturing

Smart manufacturing, also known as intelligent manufacturing, belongs to the concept of manufacturing in which advanced information and manufacturing technologies optimize production and product transactions [54]. According to Zhong et al. [55], smart/intelligent manufacturing is a modern manufacturing model that is based on intelligent technologies and science in which design, management and productions are significantly upgraded. Holubek and Kostal [56] mention that the intelligent manufacturing system consists of intelligent design, intelligent operation, intelligent control, intelligent planning and intelligent maintenance. Various smart sensors, advanced materials, intelligent devices, adaptive decision-making models and data analytics are used to facilitate the whole product lifecycle [42]. Accordingly, product quality, production efficiency and service level will be improved [57].

3.5 Intelligent manufacturing

AI provides features such as reasoning, acting and learning in an industrial manufacturing system and therefore is capable to play a key role in future manufacturing systems development efforts. With the use of AI technology as a complement of human's skill which deals more effectively with complexity, human involvement in IMS is minimized [8, 55]. The application of AI in the product lifecycle mainly consists of "intelligent cloud product design technology, intelligent cloud innovation design technology, intelligent cloud production equipment technology, intelligent cloud operation and management technology, intelligent cloud simulation and experiment technology, and intelligent cloud service guarantee technology" [42].

100% Level of human involvement 0%

Rule-based computing | Machine learning

Cognitive mode	Rule-based inference	Supervised learning	Unsupervised narrow learning	Unsupervised context-aware learning	Self-aware unsupervised learning
Natural language processing	• Spell and grammar check	• Voice to text dictation	• Personal assistant apps for basic voice-based Q&A	• Real-time dialogue and translation	• Idioms, sarcasm, nuance articulation, information
Computer vision	• Inspection of fruit defects with infrared images	• Facial recognition • Identifying verification by fingerprints	• Complex classification (e.g. video segment search)	• Vision systems for self-driving vehicles	• Digital security agents • Autonomous exploration agents
Pattern recognition	• Industrial inspection based on rules on faulty functioning	• Fraud detection (e.g. based on historical fraud patterns)	• Product recommendation based on customer preference	• Automated real-time clinical diagnosis	• Disease development and prediction of infections
Reasoning and optimization	• Diagnostic maintenance	• Predictive maintenance for machinery and vehicles	• Failure prediction in mission-critical systems	• Automated recommendation based on inputs in value chain	• Search engine answering questions instead of giving search results
	Over 5 years ago	**5 years ago**	**Current**	**2030 and beyond**	

Fig. 6. AI development and the future state of AI techniques (World Economic Forum and A.T.Kearney, 2017)

AI can utilize production optimization in manufacturing companies. For example, machine learning techniques can be employed to be used in identification tasks, where the system needs to do root cause related identifying tasks for ranking purposes to be able to define probable root causes of production challenges [58]. AI can help product designers in IMS to create multiple prototypes versions and more efficient testing [59]. However, implementing AI is not easy and requires experts for algorithm development, preparation of training data as well as translating the algorithm output into the meaningful results for humans [8]., to train the algorithm, the availability of sufficient high-quality data is required. Poor quality outputs result from badly engineered data, in other words, rubbish in, rubbish out.

3.6 Artificial Intelligence and CE

When considering the impact of AI in the role of an enabler and innovations enhancer of CE, according to Ellen MacArthur Foundation (2019), AI's role can be divided into three categories:
- By improving the sorting and disassembling product processes, remanufacturing the components and recycling materials: AI can help in closing the loops by building and improving the reverse logistics infrastructure.
- To expand innovative circular business models: AI can help to combine real-time and historical data from users and products to increase product circulation and asset utilization through pricing and demand prediction, predictive maintenance and smart inventory management.
- Design and develop circular products, components and materials: By rapid prototyping and testing through machine-learning-assisted design processes, AI can help in design out the waste for food in CE and generate the potential value of USD 127 million by 2030 [8].

3.6.1 Infrastructure optimization business model

AI can offer help into circular infrastructure optimization needs, for example by affecting material and components recycling actions and flows. AI can be used in waste-sorting improvement and efficiency by increasing the value of recycled and recovered materials [8]. Moreover, robots and automation are enablers of precise waste-sorting and therefore they can enhance current and generate new opportunities for material reuse cases, based on current materials seen as waste [60].

3.6.2 Operate innovative circular business model

In order to develop a successful and profitable innovative circular business model, organizations require functions such as pricing, marketing, sales and after-sales services as well as customer support [8]. From a digitality point of view, digitalization enabled platforms and business models to build upon platform ideologies do offer new service provision opportunities, material sharing business models, and in general the allow value generation for both, the companies and the users [61]. Dynamic pricing and matching algorithms are the two main roles of digital platforms which enhances extension of products lifecycle to achieve and retain their innovative circular objectives [8, 60, 61]. by the use of AI-based analytical model companies can make faster decisions on the next use cycle of returned products through huge data collection and analysis of data from products and customers in a more feasible way [8]. Best practices of such application models are the online flea markets in which buyers can find the more desirable prices and sellers can sell unnecessary second-hand products.

3.6.3 AI design circular product business model

According to Ellen MacArthur Foundation [8], AI technologies help to reveal high potential circular opportunities in designing circular products, components and materials. Design innovation allows cycles of reuse, repair, refurbishment and recycling of technical components as well as looping of biological nutrients. AI techniques can help scientists to evaluate a huge amount of data on the materials' properties and structure in designing a new material b rapid analyzing. In addition, AI could help the tedious work of doing material toxicity analysis for safety purposes or e.g. chemicals analysis and detection to be 1) more efficient, 2) faster and 3) economical and efficient in multiple ways trough proper algorithms developing efforts. AI can help in closing and slowing the materials loops by reducing the faults in designing and prototyping products and materials, making less waste in manufacturing processes. Looking things from the designers' point of view, according to World Economic Forum and Accenture Startegy [41], AI-based application supports them by connecting data on alternatives to harmful or hard-to-recycle materials within a product. The results of the product modularity and durability evaluation lead to an overall circularity index for the designed product. For more understanding of Below are two case examples of food and electronic companies taken from [8].

4 Results & managerial implications

This publication makes an argument for the importance of digital technologies, especially Artificial Intelligence in the context of circular product designs. The review includes a circular product design tool, which a design team could follow for gains in efforts to produce materials, whole products and their components with circular characteristics in mind, that will be beneficial for the companies and businesses as well. Additionally, smart systems will boost circularity by utilizing the finite design-related resources better, with processes such as rapid prototyping and enhanced testing. Therefore, implementing innovative AI enhancement in business models, that shall support circularity are essentials for the growth and competitiveness of the industries. Accordingly, to recognize the opportunities Artificial Intelligence could bring with it for an organization, one should understand what AI can or cannot do. Especially in their own industry context. For example, it is a good question to think about, that how the business can integrate AI and CE in all the different areas of the organizations and then take into account the product/service design elements as we have been discussing here, it is the make or break part of products life cycle circularity.

5 Limitation and further research potentials

According to the area-specific literature, there is a big gap in studies related to the role of circular product design and relating strategies and business models. Basically, the scientific publications seem to be countable in tens in this research realm and we highly suggest a systematic literature research and/or mapping study to be done in that cross-section of topics to give definite answer how big of a research gap or in what specific areas of business models and product design strategies for circularity there actually is. First of all, there could be more work to be done on infusing AI into product design courses, similarly like authors school did to infuse design thinking to software engineering teaching activities [26] or to enhance digital design process thinking teaching making more configurable products [62] to take the re-usability into account. On the other hand, more research and studies on the guidelines of designing circular products will be required, to give guidance for practical designers, as most of the studies and research are actually focused on other phases of CE such as recycling and related business models or shared platforms. Furthermore, we like to state that digitalization in CE is a novel topic which has recently gained a lot of attention from both the businesses and from researchers and it is developing rapidly. More research is also needed with deep details on what is / should be the role of AI in different phases of whole ecosystems of Circular Economies and where it fits best in different industries going towards circularity enhanced practices. For example, more detailed studies are required to figure out what challenges organizations might face when implementing digital technologies within their circular business models and what are the advantages they can gain in return. This could be helped with different community wisdom harnessing models [63] (e.g. to map reusability concept from the wide audience to teach the AI to support that sort of design features). And Different styles of new AI solution design hackathons could be used within research units and product developing companies cross-sections [64, 65] to boost new innovation generation in these fields. Additionally, case examples with ROI calculations and SWOT analysis for e.g. educational purposes would be beneficial for the academic education context. And in the bigger picture, it would make a lot of sense to look the end-user side too, e.g. if AI is used for product design, it should be connected into the solutions in use to educate the people who generate the waste to recycle the valuable resources more efficiently [66]. Finally, longitudinal studies result to reveal in which phases of CE it is more beneficial and important to utilize digitalization in each industry would help e.g. politicians to fine-tune regulations to support faster CE efforts ongoing in different industry areas.

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