Erskin Blunck
Hochschule für Wirtschaft und Umwelt Nürtingen-Geislingen (Nuertingen-Geislingen University)
MBA International Management, Faculty AVM, Nürtingen, Germany
E-mail: erskin.blunck@hfwu.de

Hedwig Werthmann
Hochschule für Wirtschaft und Umwelt Nürtingen-Geislingen (Nuertingen-Geislingen University)
MBA International Management, Faculty AVM, Nürtingen, Germany
E-mail: hedwigwerthmann@web.de

INDUSTRY 4.0 – AN OPPORTUNITY TO REALIZE SUSTAINABLE MANUFACTURING AND ITS POTENTIAL FOR A CIRCULAR ECONOMY

Preliminary communication
UDK: 004:658.5
JEL classification: Q01, L23, 014, O33

Abstract

With an increasing growth of human population, rising GDP levels and more affluent lifestyles, the human race is consuming more and more which leads to a continuously growing demand for renewable and non-renewable resources. Therefore the issue of resource scarcity is emerging, because it is questionable whether economic growth can be sustained in a world with finite natural resources. The main purpose of this work is to analyze the potential of Industry 4.0 applications to realize a more sustainable manufacturing and to create a circular economy (CE). Even if the economy nowadays is still locked into a system favoring the linear model of production and consumption, tighter environmental standards, resource scarcity and changing consumer expectations will force organizations to find alternatives. To do so, new technologies can be used to trace materials through the supply chain and to track product status during its life cycle. This development will create opportunities to accelerate the transition towards the model of a CE. Case examples show that companies are starting to capitalize on the potential of emerging technologies to rearrange production, services, business models or whole organizations in a more sustainable way. Main conclusions of this research are that there is a high potential of Industry 4.0 to ensure more sustainable manufacturing methods or a CE. This is shown by analyzing the value drivers of Industry 4.0, the potential of rearranging value chains and emerging business models. Overall, *smart products and Industry 4.0 technologies could generate significant economic, environmental and social benefits and are able to contribute to strive towards a CE.*

Keywords: Industry 4.0, Circular Economy, Sustainability

1. INTRODUCTION

With an increasing growth of human population, rising GDP levels and an improvement of lifestyles, the human race is consuming more and more. Con-sequently the demand for renewable and non-renewable resources is continuously growing (Preston & Herron 2016). This population growth and an increase of the economic well-being of a good portion of the world have been fed by unprecedented natural resource consumption and environmental impacts. Consequently the issue of resource scarcity is emerging, because it is questionable whether this economic growth can be sustained in a world with finite natural resources (Krautkraemer 2005). The diminishing amount of natural resources can be a problem especially for manufacturing companies with global supply chains. These companies may have to cope for example with increasing prices for resources and supply uncertainty (Preston & Herron 2016). Facing these problems, humans have been quite creative in finding solutions to the issue of scarce natural resources. The maybe most important approach is the development of new technologies that economize on scarce resources or that allow us to use resources that were previously uneconomical (Krautkraemer 2005). These technologies enable us to realize the productivity growth that we need to satisfy the ever-growing consumption, while not actually increasing the demand for resources significantly (Heck & Rogers 2014).

Nowadays the concept of Industry 4.0 is omnipresent. Industry 4.0 is strongly connected to megatrends like digitization and connectivity (Horx 2015; Heuer 2015). Within Industry 4.0 production is connected to the latest communication and information technology (Bundesministerium für Wirtschaft und Energie 2016). Beyond all competitive advantages through for example an improvement of efficiency and flexibility, also an efficient use of resources should be considered. At this juncture production processes within Industry 4.0 should be seen as holistic balanced circuits, which guide and shape the new industrial production (Arbeitskreis Industrie 4.0 2012, p. 30-31). Environmental pollution and shrinking resources have incrementally increased pressure on industrial businesses. These circumstances confront manufacturing industries to cope with the pressure of environmental regulations set by governments, challenges of resource price volatility, because of scarce resources, and risks in resource supply. A circular economy could be the solution to harmonize ambitions for economic growth and environmental protection, where the circular economy is understood as realization of a closed loop material flow in the whole economic system (Lieder & Rashid 2015, p. 36-51). Here the development towards Industry 4.0 provides immense opportunities for the realization of sustainable, eco-friendly and resource saving manufacturing (Stock & Seliger 2016, p. 536-541). The main purpose of this work is to analyze the potential of Industry 4.0 applications to realize a more sustainable manufacturing and the opportunities provided by the fourth industrial revolution to create a circular economy. Therefore the questions should be answered: Which potential of sustainability does Industry 4.0 have to ensure a cleaner production? And is even the implementation of a circular economy possible or facilitated by using the technologies and changes which emerge through the fourth industrial revolution?

1.1. Industry 4.0

The first time the notion "Industry 4.0" (derived from the German term "Industrie 4.0") was mentioned in public, was at the "Hannover trade fair" in 2011, Germany (Kagermann, Lukas, & Wahlster 2016). The following initiative set by the Federal Ministry of Education and Research, Germany (BMBF, Bundesministerium für Bildung und Forschung), also called "Industry 4.0", intends to encourage the German manufacturing industry to prepare for the future of production (Bundesministerium für Bildung und Forschung 2016). In the meantime the term Industry 4.0 is also widely used across Europe. Consequently the term Industry 4.0 describes nowadays in general the digital transformation of the manufacturing industry, which is accelerated by exponentially growing technologies, like for example intelligent robots, autonomous drones, sensors and 3D-printing (Bundesministerium für Bildung und Forschung 2016). Other terms appearing along with Industry 4.0 are the "digital transformation", the "Internet of Things" or the "Industrial Internet (of Things)". These terms are also applied interchangeably with the notion Industry 4.0 and the last two are used more commonly in the United States and the English-speaking world (Deloitte 2015, p. 3). Furthermore other companies like for example Cisco are using the term "Internet of Everything" (De Bernardini 2015). All these notions are referring to similar technologies and applications, but can have different origins and meanings. Whereas Industry 4.0 is focused specifically on the manufacturing industry, terms like the Internet of Things, the Digital Revolution and the Internet of Everything are more focused on enabling and accelerating the adoption of internet-connected technologies across industries, both manufacturing and non-manufacturing. Nevertheless, what all these terms and concepts have in common is the recognition that traditional manufacturing methods are run through a digital transformation (Deloitte 2015).

1.2. Definitions of Important Elements of Industry 4.0

Referred to the vision of Industry 4.0 it is still based on automation technology (e.g. robots), but these technologies are now connected via sensors and other control elements to link the real and the virtual world forming cyber-physical systems. These cyber-physical systems are then able to cross-link all productive entities to each other through the internet. This communication of physical objects without any human interaction is known as the Internet of Things. A huge amount of data arising out of that interaction (big data), could be stored in clouds and converted into smart data in order to filter the information really needed and to evaluate the generated data in a proper way (see Figure 1). If we take all these technologies together we will be able to form the smart, digital factories of the future.

A cyber-physical system (CPS) describes the technological basis of IT in combination with the physical world, meaning they connect information technology with mechanical and electronic elements. These systems of collaborating computational entities are therefore in a steady intensive connection with the surrounding physical world and its ongoing processes (Monostori 2014, p. 9-13). Therefore open and cross-linked systems arise, which are able to collect data within various situations of the physical world. In addition to that they interpret data and make them available. These systems can react via actuator systems to processes within the physical world and therefore they can influence the behavior of equipment, things and services (Geisberger & Broy 2012, p. 9). Such CPSs can also be used within manufacturing systems, where the intelligent cross-linking is for example realized by embedded sensors, processors, software and connectivity in products, coupled with a product cloud in which product data is stored and analyzed. These data can be used to improve product functionality and performance (Stock & Seliger 2016, p. 536-541).

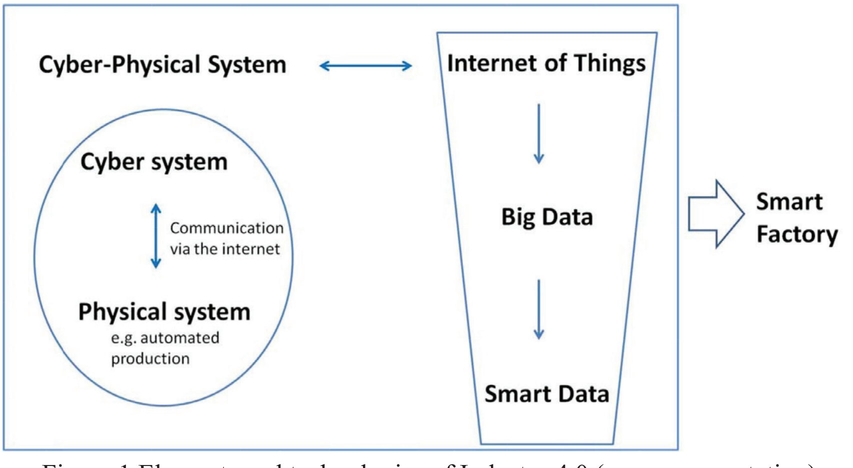

Figure 1 Elements and technologies of Industry 4.0 (own representation)

The Internet of Things is described in various ways by companies and organizations. But most commonly it is described as an "ecosystem of technologies monitoring the status of physical objects, capturing meaningful data, and communicating that information through networks to software applications". The recurring topics in all definitions of the Internet of Things include smart objects, machine to machine communication (M2M) and radio-frequency-technologies (Thrasher 2014). Through the Internet of Things it is possible to connect everyday objects to remotely determine their state via information systems, which collect up-to-date information on these physical objects and processes continuously. Equipped with own sensor- and actuator-technology these smart real objects are able to integrate each other to form complex, autonomous systems. Some producers are already talking about the Internet of Everything (IoE), which is embedding humans, processes, things and data into an all-embracing network (Hackmann 2013). Through Industry 4.0 applications there is a change of the whole industrial value chain through an increasing digitalization and networking. The huge and continuously produced amount of data through the ever growing use of sensors, networked machines in CPS and the development towards an industry with smart factories is called big data. These sensor-generated, networked data from a wide variety of sources are unstructured. To make use of these data, for example to generate forecasts and enable companies to take fact-based decisions, it is important to consolidate and evaluate these data in an intelligent way (Sauter et al. 2015, p. 5). Consequently companies must face the challenge to develop smart predictive informatics tools to manage big data (Monostori 2014, p. 9-13; Lee, Kao, & Yang 2014, p. 3-8). If this challenge will succeed then smart factories producing smart products with the aid of CPS and the IoT, collecting smart data at each step of production, will be enabled to self-organize each required manufacturing step throughout the whole production process or even the whole value chain.

1.3. Smart Manufacturing in the Smart Factory

According to the vision of Industry 4.0 the future of production could look like the following: There will be communication via software and networks over the whole vertical value chain (product development, production, services). Smart machines will exchange information and instructions in real-time with smart products as well as with individuals across the whole value chain and the overall product life cycle (PLC). Through sensors and control elements it will be possible to link plants, fleets, networks and human beings. Machines itself will continually share information about current stock levels, problems, faults, and changes in orders or demand levels. Furthermore processes and deadlines are coordinated to raise efficiency and throughput times are optimized. Consequently an increase in quality throughout the whole PLC will take place. In total this will create a production system with autonomous control and optimization (Siemens 2014; Deloitte 2015, p. 4).

Until now the smart factory is a great revelation of future developments in manufacturing facilities. Nevertheless, technologies need to mature and the concept still needs to progress before reaching its full potential and practical application in an industrial production set up (Radziwon et al. 2014).

2. IMPACTS OF INDUSTRY 4.0 APPLICATIONS

Industry 4.0 can have many impacts, positive as well as critical ones. When we talk about Industry 4.0 we mainly talk about it in a technical context, but the fourth industrial revolution has also massive impacts on the whole organization and through the application of CPSs technical processes and business processes fuse. Therefore the topic should be also considered from the business administrative point of view.

In the following section a selection of the various impacts of Industry 4.0 technically and economically speaking are analyzed and defined. These economic benefits also include various value drivers indicated by researchers and strategy consulting firms. When looking at these value drivers and trying to op-timize and work with them, there is high potential to accomplish economic im-provement within business and manufacturing processes. All these impacts described in the following section will then lead to an analysis how Industry 4.0 technologies can contribute to find sustainable manufacturing solutions or how they can aid to establish a circular economy.

2.1 Economic benefits by using Industry 4.0 applications

McKinsey summarized the main drivers of creating value and enjoying economic benefits within its "Digital Compass", where they defined eight value drivers. These drivers will create value for companies and customers at each step of value creation across the entire PLC. By using these value drivers, it is possible to describe economic benefits for companies applying Industry 4.0 concepts in more depth. These value drivers will be explained in the following regarding how they impact the performance of companies concerning Industry 4.0 having in mind the objective to maximize value (McKinsey 2015, p. 22-27).

<u>Using resources and optimizing processes:</u> The possibilities to improve processes and the consumption of materials when using the concepts of Industry 4.0 are versatile. It is possible to decrease material costs by less defective goods and optimize processes (in speed or yield) via the use of cyber-physical systems, which allow the observation of processes in real-time. Through the use of these technologies it will be possible to react to events in the physical world in an automatic and fast way. Therefore the improvement of manufacturing processes including the optimization of material consumption will drive value and will make it possible to increase productivity by 3-5 percent (McKinsey 2015, p. 24; see Figure 2).

<u>Utilization of assets:</u> The optimal use of a companies' machinery park is supported by Industry 4.0 based technologies, which enable for example predictive maintenance. Through the permanent, remote monitoring of machinery conditions it becomes possible to reduce machine downtimes or changeover times by an early detection of possible problems and continuous maintenance. The avoidance and early correction of defects can therefore save costs and drive production throughput, which consequently drives value (McKinsey 2015, p. 24). According to analyses the use of predictive maintenance enables to decrease total machine downtime by 30-50 percent and to increase machine life by 20-40 percent (see Figure 2).

<u>Labor productivity</u>: An increase of the productivity of labor can significantly drive value. The improvement of labor productivity can be realized

by using the new technologies of Industry 4.0, which make it possible e.g. to reduce waiting times between different production steps in manufacturing or by accelerating the R&D process (e.g. through 3D-printing). Furthermore the burden or complexity of tasks can increase the speed of manual production steps executed by workers (McKinsey 2015, p. 25). An example for such assistance within production processes is the German company Festo, where human-robot collaborations work in close proximity to each other (Festo AG & Co. KG 2015).

Management of inventories: A proper management of inventories is very important, because too much inventory leads to great capital costs. By applying Industry 4.0 levers, drivers of excess inventories can be targeted by addressing problems like unreliable demand planning and overproduction. This becomes possible e.g. through real-time supply chain optimization (McKinsey 2015, p. 25). Through technologies like systems which automatically reorder if necessary, costs for inventory holding can be reduced by 20-50 percent (see Figure 2).

Quality improvement: Industry 4.0 applications facilitate the improvement of product and process quality by using real-time problem solving, advanced process control or real-time error corrections to decrease unstable manufacturing processes, rework and consequently extra costs (McKinsey 2015, p. 26). By using these approaches a saving of costs related to suboptimal quality of about 10-20 percent could be achieved (see Figure 2). For example Siemens was able to decrease the defect rate to a minimum through the use of advanced technologies emerging with the fourth industrial revolution (Siemens 2014a).

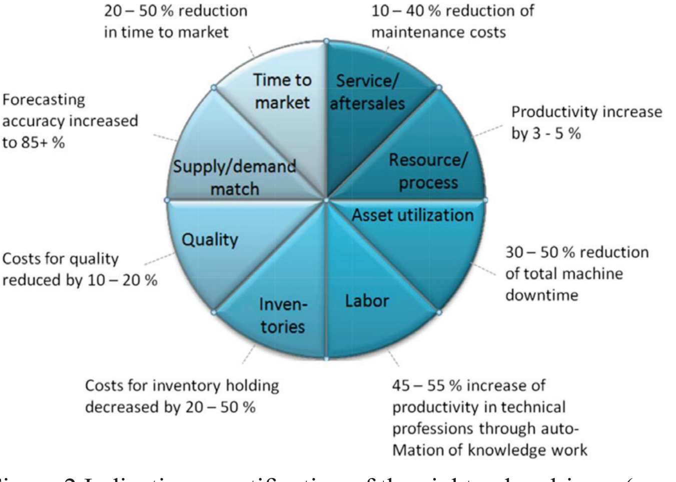

Figure 2 Indicative quantification of the eight value drivers (own representation according to McKinsey 2015, p. 25).

Match of supply and demand: To prevent from waste by unnecessary inventory and storage cost, a perfect understanding of customer demand in terms of quantity and product features lead to a much better predictability through new possibilities like e.g. crowd forecasting based on advanced analytics (McKinsey 2015, p. 26). The use of such technologies can increase the accuracy of demand forecasting to more than 85 percent (see Figure 2).

Reducing time to market: Being the first supplier on the market with a new product can create value in terms of increased revenues and less competition. New technologies emerging with Industry 4.0 enabling faster and cheaper R&D processes, e.g. concurrent engineering or rapid prototyping by using 3D-printing can significantly reduce the time to market (McKinsey 2015, p. 26). The use of such technologies can reduce the time to market by 30-50 percent (see Figure 2).

Service and aftersales: Innovative services lead to new possibilities of repairing products and to the chance to keep them longer operational. Product manufacturing can be more cost effective, when machines get a longer operational time. This is possible e.g. through remote maintenance or virtually guided self-service. In this case it is possible to carry out error diagnosis and even repair without the necessity of a technician visiting the site (McKinsey 2015, p. 27). In average maintenance costs could be reduced by about 10-40 percent through the use of remote and predictive maintenance (see Figure 2).

All eight value drivers are showing high improvement potential, enabled by Industry 4.0, within already existing production systems. To activate these value drivers and really exploit the potential they offer, it is necessary to prepare the company to take part in the fourth industrial revolution.

2.2. Transformation of Value Chains

Industry 4.0 is characterized by an increasing digitization and interconnection of products, business models and value chains. A successful implementation of digital manufacturing solutions as described (see 1.3), entails a fluid digital communication across the whole value chain – this continuous flow of data is also called "digital thread" (Nanry et al. 2015). Customers will be at the center of the changes to value chains, products and services and everything will be increasingly customized (Geissbauer et al. 2016, p. 8).

Generally the increasing digitization simplifies the outsourcing of business processes along the value chains. Therefore there won't be classical value chains with clearly defined boundaries between the company´s internal functions and external areas within Industry 4.0. Shorter PLCs, smaller lot sizes and an intensified individualization of products require a fast and efficient cooperation within and between all involved functions and corporations. Through Industry 4.0 applications and their ubiquitous exchange of information, internal and external boundaries will merge and classical borders of individual enterprises will be shifted (Wischmann et al. 2015, p. 15). Industry 4.0 digitizes and integrates processes vertically across the whole organization through all functions, from product development and purchasing through manufacturing, logistics and aftersales. In addition to that horizontal integration stretches beyond the internal operations. Here also suppliers, customers and all key value chain partners are integrated (Nanry et al. 2015). A third dimension is the end-to-end engineering across the whole PLC (Stock & Seliger 2016, p. 536-541; Acatech 2013, p. 6; Deloitte 2015, p. 6).

In order to deliver the goals of Industry 4.0 and gain improved competitiveness, the features of all three dimensions should be implemented.

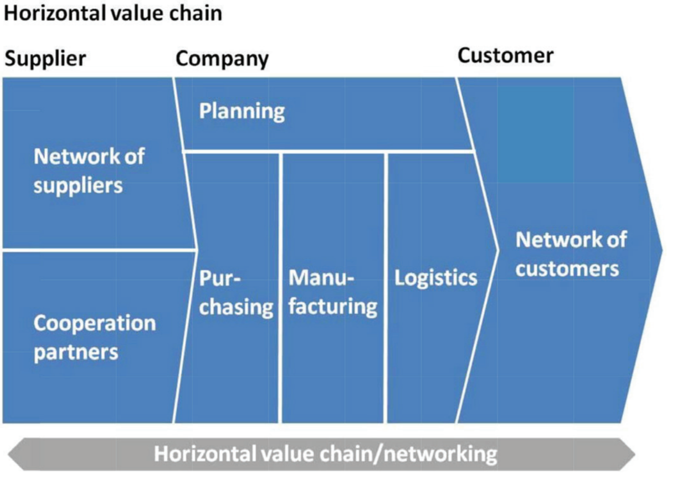

Figure 3 Horizontal value chain (own representation according to Koch et al. 2014, p. 17): Horizontal integration across the value creation networks/supply networks means that also external functions like suppliers and customers are part of the value chain.

The horizontal integration characterizes the cross-company and company-internal (across company departments) smart networking and digitalization throughout the value chain of a PLC and between value chains of neighboring PLCs (Stock & Seliger 2016, p. 536-541). The digitalization of the horizontal value chain integrates and optimizes the flow of information and flow of goods from the customer over the whole corporation to the point of the supplier and vice versa (see Figure 3). Within this approach all company-internal areas (e.g. purchasing, production, logistics) will be connected and regulated foresightful together with all external partners being part of value creation (Koch et al. 2014, p. 16). Within Industry 4.0 horizontal integration will enable the smart factory to adapt constantly to new circumstances, e.g. to the order volume or the availability of materials. Therefore an automatic optimization of production processes becomes possible through the integration of suppliers and customers into the value chain (Lichtblau et al. 2014, p. 11).

The vertical integration specifies the intelligent cross-linking and digitalization within the different hierarchical levels of a value chain. This will enable digital order processes and customer specific product development, where an automated transfer of data into an integrated planning and manufacturing system can be assured. Furthermore the associated value chain activities such as marketing and sales or technology development are integrated (Koch et al. 2014, p. 11; Stock & Seliger 2016, p. 536-541; see Figure 4). Within this vertical inte-gration it becomes possible to have flexible and reconfigurable production struc-tures, which can be adapted to each specific customer order or even to changing market requirements. These features are key enablers for manufacturers to stay competitive within highly volatile markets and it will allow them to reach fast and fault-free production (Stock & Seliger 2016, p. 536-541).

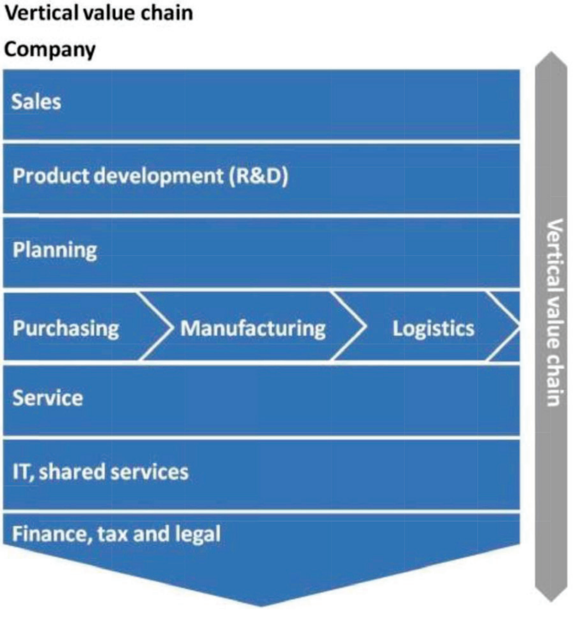

Figure 4 Vertical value chain (own representation according to Koch et al. 2014, p. 17): Vertical integration and connected production systems mean, that all functions along a company´s vertical value chain are integrated.

End-to-end engineering across all phases of a PLC describes the intelli-gent cross-linking and digitalization throughout the whole PLC, from the pro-curement of raw materials, the use of the product until its end of life (Stock & Seliger 2016, p. 536-541). This integrated engineering along the whole value chain promises high optimization potential. Within such a way of engineering all entities being part of the engineering process will be provided with real-time in-formation. The advantage is that it encompasses both, the manufacturing process and the manufactured product, when engineering the associated manufacturing system at same time as product is engineered (see Figure 5).

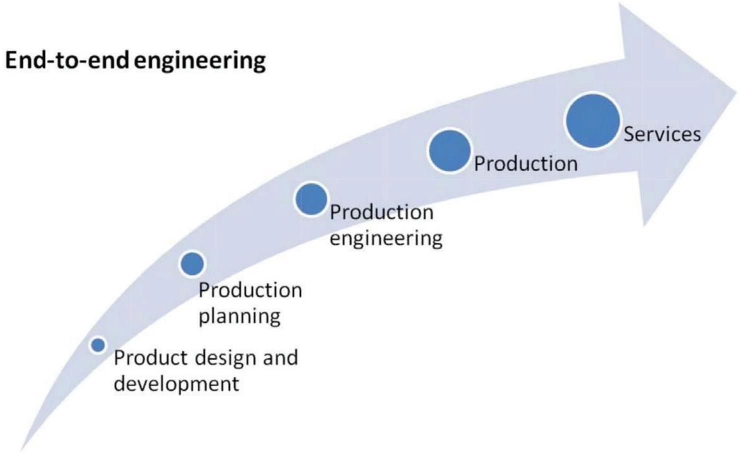

Figure 5 End-to-End Engineering (own representation according to Acatech 2013, p. 31): Digital patency of the engineering across the value chain.

2.3. Emerging Business Models

"A business model is defined by two things: how the organization creates value for its customers (the customer value proposition) and how it captures that value (how it makes money). Digital transformation changes both." (Iansiti & Lakhani 2014). That means Industry 4.0 has an effect not only on the product and its production, but Industry 4.0 will also have an effect on the business model, because in the future producers will offer their products in new ways (Messe München GmbH 2015). Through the considerable increase of the digitization of value chains and the integrated use and analytics of data, Industry 4.0 also enables the creation of new markets by reinventing the way things are done. Established business models will become more efficient and customer-oriented due to the increased connectivity and analytical abilities (Koch et al. 2014, p. 4, p. 33). Present business models will change and new, disruptive, digital business models enabling e.g. mass customization will emerge. Similar to the concept of Re-Engineering business models and concepts can be imagined in a radically different way, based on the new possibilities of Industry 4.0.

In Industry 4.0, new evolving business models are highly driven by the use of smart data for offering new services. In this context, selling the functionality and accessibility of products instead of only selling the tangible products will be a leading concept (Stock & Seliger 2016, p. 540).

3. THE CONCEPT OF A CIRCULAR ECONOMY

Within the last few years the idea of a circular economy (CE) is getting increasing attention worldwide. The concept is seen as a way to overcome the current production and consumption model, which is based on continuous growth and increasing resource consumption. A closed-loop design of production patterns within an economic system, like the CE approach, could increase the efficiency of resource use and reduce urban and industrial waste. Consequently a CE could pave the way to achieve a better balance between the three pillars of sustainability: economy, environment and society (Ghisellini et al. 2016). The concept of the circular economy and what we understand by it nowadays is described by the Ellen MacArthur Foundation, an association to accelerate the transition towards a CE, as the following:

"A circular economy is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times (…). As envisioned by the originators, a circular economy is a continuous positive development cycle that preserves and enhances natural capital, optimizes resource yields and minimizes system risks by managing finite stocks and renewable flows. It works effectively at every scale." (Ellen MacArthur Foundation 2015).

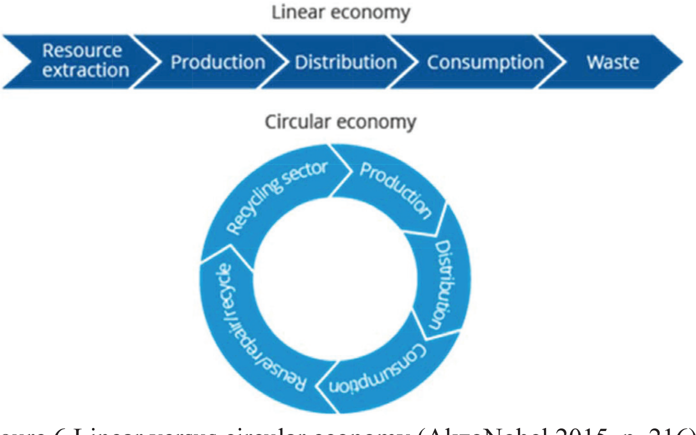

Figure 6 Linear versus circular economy (AkzoNobel 2015, p. 216)

By this design, the CE replaces the end of life idea. Through the superior conception of materials, products, systems and business models, the CE enables restoration, a shift towards renewable energy and the elimination of the use of toxic materials and waste production. Consequently CE aims to design out waste at its core, because products are designed and optimized for a cycle of disassembly and reuse. These tight product and component cycles define CE and distinguish it from disposal and recycling. (See also Figure 6)

4. INDUSTRY 4.0 APPLICATIONS AS ENABLER FOR A CIRCULAR ECONOMY

Within the following the potential of Industry 4.0 applications will be analyzed with regard to sustainable manufacturing and the circular economy. It will be assessed how Industry 4.0 elements are able to ease the implementation of CE principles. Furthermore interconnected value chains and emerging business models will be evaluated towards their potential to drive sustainability.

4.1. Potential of Emerging Technologies along Value Drivers

A sustainability-oriented decentralized organization for a CE in a smart factory focuses on efficient allocation of products, materials, energy and water by taking into account dynamic constraints of the CPS, e.g. of smart logistics, smart grid, self-sufficient supply or the customer (Stock & Seliger 2016, p. 540). Such a concept towards holistic resource efficiency in the sense of a CE is seen as one of the essential advantages of Industry 4.0 (Kagermann et al. 2016). In a world of perfect information it is possible to manufacture even more efficiently than automation already enabled. It becomes possible to use fewer resources, while getting the same results as before and production becomes more flexible. Consequently smaller production batches are possible. Such efficiency improvements can be also used for the implementation of a circular economy, even though this might only be the starting point for more radical circular economy innovations in the coming years. Within Industry 4.0 physical production processes and information and communication technology grow more closely together. Embedded systems, sensors, actuators, mobile devices and production facilities are able to communicate with each other via the internet. Through this development production processes get transparent and easily influence able. In addition to economically measurable success factors through the implementation of Industry 4.0 applications, it is important for companies to also consider environmental and social impacts, like the future of work and resource efficiency, to ensure durable competitiveness (Gabriel & Pessl 2016, p. 131). Information is of utmost importance to ensure that businesses all over the world are able to make the right decisions, to eradicate waste and to use resources effectively. Industry 4.0 and its technologies like the IoT can play a key role in providing such valuable information about things like energy use, underutilized assets and material flows (Ellen MacArthur Foundation 2016, p. 9). When technologies were used the right way, Industry 4.0 is supposed to lead to a highly adaptive and thereby resource-efficient and ergonomic production.

Within the following section the potential of Industry 4.0 technologies to manufacture in a more sustainable way and to establish an economy according to CE principles will be exemplary described using the value drivers outlined in chapter 2.1.

<u>Using resources and optimizing processes</u>. Enabled by the IoT and CPSs it is possible to observe processes in real-time. The interconnection of machines,

products and humans and the omni-present information about everything makes it possible to react in a very fast, efficient and fully automated way to every circumstance during production. If everything gets traceable also the consumption of resources gets increasingly transparent within these advanced manufacturing processes. Therefore it will be able to exactly assess the amount of resources needed for each production step. Processes with excess resource consumption can be identified and optimized or eliminated. Through the incorporation of "smart materials", equipped with sensor- and actuator-technology, these resources can be observed not only during the production process itself, but also throughout the whole life cycle of the product they are incorporated in. The observation of state and location of valuable materials (e.g. rare metals used in electronic parts) by using RFID-technology will reduce waste and will increase the reuse of these scarce resources. This will enable or at least ease to hold technical and biological nutrients within their cycles. The observation of process conditions in real-time holds not only for the consumption of classical input materials. It also makes it possible to trace for example energy and water consumption during each step of production. Furthermore processes can be analyzed in detail according to the time each step of production needs. In addition to optimization of the production time does not only save time, but shorter production processes typically consume less resource like energy. Within Industry 4.0 processes will be able to monitor, to be aware, to predict, to optimize and to configure themselves (Song & Moon 2016, p. 5-6). Consequently processes can be designed more sustainable and ease to establish an economy according to CE principles with the help of Industry 4.0 applications. This improvement of manufacturing processes including the optimization of material consumption will drive value and will make it possible to increase productivity.

Utilization of assets: Within most factories manufacturing equipment is a capital good with a long use phase of up to 20 or more years. Retrofitting of assets enables an easy way of upgrading existing manufacturing equipment with sensor and actuator systems as well as with the related control logics. This is a cost-efficient way to use Industry 4.0 technologies and make assets "intelligent". Like that retrofitting enables the realization of CPS throughout a value creation module, such as a factory, with already existing manufacturing equipment (Stock & Seliger 2016, p. 540). Through the use of Industry 4.0 technologies knowledge about the assets' location, condition and availability can be collected. The information about the location and availability of an asset is especially important for businesses that have mobile assets and will enable them to use their assets more effectively. In addition to that it is an important facilitator of sharing models, which contribute to a sustainable use of resources. The collection of data to monitor an asset´s condition will enable users to define thresholds or rules to initiate actions or notifications that allow condition based reactions. This will make e.g. predictive maintenance and replacement of failing components (prior to asset failure) possible and will enable to minimize downtimes (Ellen MacArthur Foundation 2016b, p. 28-31).

Therefore the use of Industry 4.0 technologies enables to extend the use phase and facilitates the application of manufacturing equipment in a new use phase according to CE principles. Consequently this can essentially contribute to the economic and environmental dimensions of sustainability, meaning intelligent assets are already presenting solutions to many resource challenges. (Stock & Seliger 2016, p. 540)

Labor productivity: Within Industry 4.0 humans will still be the organizers of value creation (VDI/VDE & GMA 2014). Nevertheless the needs for skills will change and different competences will be important. Routine jobs will cease to exist and through an accelerating digitization new functions will get more complex and new occupational areas will arise (McKinsey, Stifterverband für die Deutsche Wissenschaft e.V. 2016, p. 7). To cope with the social challenge of Industry 4.0 in a sustainable way the training efficiency of workers can be improved by combining new information and communication technologies (ICT).

Management of inventories: Industry 4.0 applications definitely ease the management of inventories. Through real-time data about stock levels it is possible to reduce waiting times, inventory costs and storage space (Song & Moon 2016, p. 16). This hides a lot of potential also with regard to sustainable economic activities, because too much inventory leads not only to great capital costs, but also to unused and excess resources. Additionally, Industry 4.0 technologies can minimize unreliable demand planning and overproduction. An intelligent system, which automatically reorders if the minimum fill level is reached will avoid surplus materials and will lead to a real-time optimization of the supply chain (McKinsey 2015, p. 25). Such reductions of inventory levels lead to decreased energy needs for the proper storage of the inventory as well as less waste created by materials turning old or outdated due to technical progress. Consequently optimal manufacturing component utilization can be achieved by using Industry 4.0 applications, leading to ultimate sustainable benefits (Song & Moon 2016, 16).

Quality improvement: Quality improvement of products and processes by using real-time problem solving, advanced process control or real-time error corrections hide also potentials for a more sustainable manufacturing. As described previously, it becomes possible to design manufacturing sequences more resource-efficient regarding to material, water and energy consumption through process optimization. Therefore the consumption of these resources can be minimized through the use of Industry 4.0 technologies. In addition to the optimization of processes, an increased product quality will lead to less rework and less waste during the production process. This will also reduce waste as well as production time. Furthermore products of higher quality will be able to be kept much longer within the operational phase, meaning the PLC and its use phase can be extended. Customers will need new products less frequently.

Match of supply and demand: As already mentioned within the sub item "Management of inventories", Industry 4.0 technologies can minimize unreliable demand planning and overproduction. More accurate demand forecasts as enabled by Industry 4.0 applications lead to reductions in waste, because needed input materials could be projected more accurate (which will reduce inventory) and overproduction can be reduced. This will decrease the need for large amounts of raw material within the supply chain and transportation, because only on-demand spare parts are created. Accurate demand forecasts will also ease the implementation of CE principles, because also the reuse and preparation of already used materials can be planned more precise. If companies can be sure to cover actual demand by cycling of already used materials or the reuse and remanufacturing of products, fewer resources will be extracted for the production of entirely new goods. (See Figure 7)

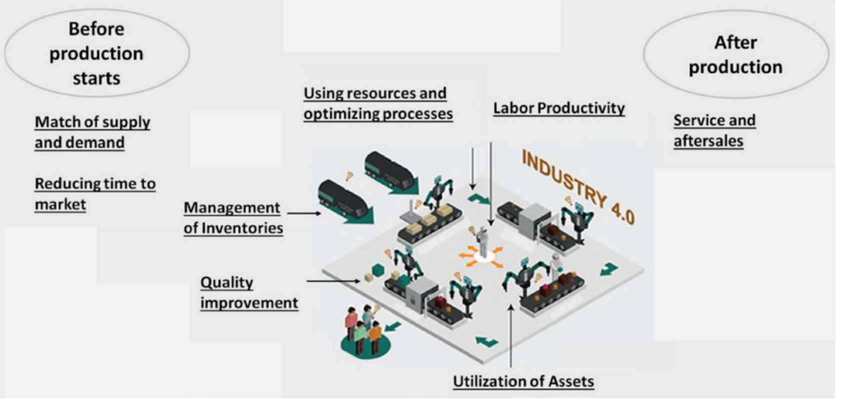

Figure 7 Industry 4.0 is changing traditional manufacturing relationships (modified according to Rüßmann et al. 2015): The potential of emerging technologies to manufacture more sustainable exemplarily outlined using the value drivers described in chapter 2.1.

Reducing time to market: New Industry 4.0 technologies enable faster and cheaper R&D processes. This will be possible through procedures like concurrent engineering or rapid prototyping, also called additive manufacturing, by using 3D-printing. Additive manufacturing has the potential to create geometrically complex parts that require a high degree of customization, using less material and producing less waste. The ability of additive manufacturing to build parts directly from a digital representation makes it an excellent alternative compared to traditional methods. Besides the fact that additive manufacturing produces less waste because parts are stamped or sculpted out of larger pieces of material, no special tooling or fixtures are required. This makes the method largely material efficient when comparing it with traditional processes. Furthermore the material used has less impact over its life cycle, resulting in a lower carbon footprint and less embodied energy (Mani et al. 2014, p. 419-421). In addition to the more sustainable technologies used to realize the reduction of time to market, it also means faster learning if a product or process turns out to be less suitable for a CE. This means that the continuous improvement cycles are accelerated to the benefit of using the latest technology and practices to implement a CE.

Service and aftersales: Through Industry 4.0 new business models will emerge. These models will bring manufacturer or service provider and customer more closely together. There will be models where products or services will be only leased or borrowed instead of being bought. Consequently service and aftersales will get more and more important within these models. This also hides potential for sustainable improvements. On the one hand products provided can be kept longer operational by the support through maintenance services and repairs. On the other hand it will be easier for the provider to get back products after their use phase, because products and parts can be traced by the provider over the whole PLC. Consequently products can be recycled or remanufactured and parts can be reused and kept within a circular economy.

4.2. Other Potentials of Industry 4.0 for a Circular Economy

Interconnected Value Chains: When production systems become even more digital, intelligent and connected, value chains become increasingly integrated and transparent. This enables to extend the product lifecycle management beyond the producers' boundaries and to cover the actual quality of products also in the use phase. As described in chapter 2.2 all three dimensions, which are the horizontal value chain, the vertical value chain and the end-to-end engineering, will be changing within Industry 4.0. In general Industry 4.0 technologies like RFID enable a greater visibility into the supply chain, because everything becomes traceable. This makes it possible for companies to e.g. efficiently track and manage inventories, consequently reducing unnecessary transportation requirements and fuel usage, which becomes important when thinking about a more sustainable design of value chains (Sundmaeker, Guillemin, Friess, & Woelfflé 2010, p. 56).

Potential of Emerging Business Models: The development of Industry 4.0 technologies can be exploited for the creation of new sustainable business models. Sustainable business models significantly create positive or reduce negative impacts for the environment or society (Bocken, Short, Rana, & Evans 2014, p. 42-56) or they can even fundamentally contribute to solving an environmental or social problem. Additionally, sustainable business models are necessarily characterized by competitiveness on the long-run (Schaltegger & Wagner 2011, p. 222-237). Referring to CE and sustainable manufacturing, new categories of business models as indicated in chapter 2.3 provide opportunities to generate growth in revenues and employment for people without linear increase of physical materials consumed. Improvement in the usage of data, machinery equipment, software and other resources can reduce the need for such limited resources and reduce the ecological footprint of production. Additionally, sustainable business models are necessarily characterized by competitiveness on the long-run (Schaltegger & Wagner 2011, p. 222-237). Referring to CE and sustainable manufacturing, new business models provide opportunities to generate growth in revenues and employment for people without linear increase of physical materials consumed. Improvement in the usage of data, machinery equipment, software and other resources can reduce the need for such limited resources and reduce the ecological footprint of production. But not only Industry 4.0 presents new business models, also the concept of the circular economy provides innovative changes. Ideas of CE as extending the lifecycles of product and assets and moving away from finite resource use at production stage and then recycling at the end of life, is leading to several business models, which is however beyond the scope of this paper.

5. CONCLUSIONS AND OUTLOOK

The economy nowadays is locked into a system where a lot still favors the linear model of production and consumption. However, this lock-in is getting weaker under the pressure of several disruptive trends. When finding new ways considering these changes, advanced information technology is seen to be able to provide the characteristics and qualities needed. These technologies, which also emerge within the new age of manufacturing (also called Industry 4.0) can be used to trace materials through the supply chain, to identify products and material fractions and to track product status during use. To overcome the difficult environmental, economic and social problems of today and tomorrow, system thinking skills, in conjunction with a comprehensive, integrated understanding of technology and data will be essential. These advances in technology will create ever greater opportunities to accelerate the transition towards the model of a CE.

To answer the research questions asked in the beginning: there is a high potential of Industry 4.0 elements to ensure more sustainable manufacturing methods, which is shown exemplarily when analyzing the value drivers of Industry 4.0 in section 4 and the potential of rearranging value chains. Also emerging business models hold opportunities to reshape organizations in a resource-efficient way. These descriptions also show that even the implementation of a CE will be easier to realize when exploiting the technologies and changes which emerge through the fourth industrial revolution.

Overall, smart products and Industry 4.0 technologies could generate significant economic, environmental and social benefits and therefore are able to contribute to strive towards a CE. It opens the way for businesses to capture the value of untapped waste streams and turn it into wealth. Such an economic system will be able of ushering in a new area of growth and development, which represents a real opportunity to redefine the relationship of the present economy with resources and to shape a future which is socially, environmentally and economically sustainable. This system will be decoupled from resource constraints, where nature is the perfect example of such principles in action.

REFERENCES

Acatech RWTH Aachen Universität Paderborn, 2016. Industrie 4.0 - Internationaler Benchmark, Zukunftsoptionen und Handlungsempfehlungen für die Produktionsforschung.

AkzoNobel, 2015. AkzoNobel Report 2015 - The Circular Economy. , p.216. Available at: http://report.akzonobel.com/2015/ar/servicepages/downloads/files/akzonobel_report15_entire.pdf.

Arbeitskreis Industrie 4.0, 2012. Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0. , pp.30–31.

De Bernardini, L., 2015. Industry 4.0 or Industrial Internet of Things—What's Your Preference? *Automationworld.com*. Available at: http://www.automationworld.com/industry-40-or-industrial-internet-things-whats-your-preference [Accessed October 22, 2016].

Bocken, N.M.P. et al., 2014. A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production*, 65, pp.42–56.

Bundesministerium für Wirtschaft und Energie, 2016. Was ist Industrie 4.0. *Plattform Industrie 4.0*. Available at: http://www.plattform-i40.de/I40/Navigation/DE/Industrie40/WasIndustrie40/was-ist-industrie-40.html [Accessed October 20, 2016].

Cisco Systems Inc., 2016. Smart+Connected Personalized Spaces. *cisco.com*. Available at: http://www.cisco.com/c/en_in/solutions/industries/smart-connected-communities/smart-connected-personalized-spaces.html [Accessed January 20, 2017].

Deloitte, 2015. Industry 4.0. Challenges and Solutions for the Digital Transformation and Use of Exponential Technologies. *Deloitte*, pp.1–2, 3, 4, 6, 12, 14.

Ellen MacArthur Foundation, 2015. Circular Economy Overview. *ellenmacarthurfoundation.org*. Available at: https://www.ellenmacarthurfoundation.org/circular-economy/overview/concept [Accessed November 24, 2016].

Ellen MacArthur Foundation, 2016. Intelligent Assets: Unlocking the Circular Economy Potential. , p.27.

Evans, D., 2011. The Internet of Things - How the Next Evolution of the Internet is Changing Everything. , p.3. Available at: http://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf.

Festge, R., 2015. "Industry 4.0": How European companies can really benefit. *EurActive.com*. Available at: https://www.euractiv.com/section/digital/opinion/industry-4-0-how-european-companies-can-really-benefit/ [Accessed November 18, 2016].

Festo AG & Co. KG, 2015. Scharnhausen Technology Plant - Shaping the future to be versatile. *festo.com*. Available at: https://www.festo.com/group/en/cms/10967.htm [Accessed May 3, 2016].

Frankfurter Allgemeine Zeitung, 2016. Die intelligente Fabrik hat Laufen gelernt. *Frankfurter Allgemeine Zeitung*, p.24.

Gabriel, M. & Pessl, E., 2016. Industry 4.0 and Sustainability Impacts: Critical Discussion of Sustainability Aspects with a Special Focus on Future of Work and Ecological Consequences. *Annals of the Faculty of Engineering Hunedoara*, pp.131–136. Available at: http://search.proquest.com/openview/1150ebdb5a42a699c7f77b433a236a43/1?pq-origsite=gscholar&cbl=616472.

Geissbauer, R., Vedsø, J. & Schrauf, S., 2016. Industry 4.0: Building the Digital Enterprise. , pp.6, 8–9, 12, 27. Available at: https://www.pwc.com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016.pdf.

Ghisellini, P., Cialani, C. & Ulgiati, S., 2016. A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems. *Journal of Cleaner Production*, 114, pp.11–32.

Hackmann, J., 2013. Internet of Things (IoT) in der Praxis - Industrie 4.0 ist das Internet der Ingenieure. *Computerwoche.de*. Available at: http://www.computerwoche.de/a/industrie-4-0-ist-das-internet-der-ingenieure,2538117 [Accessed October 22, 2016].

Heck, S. & Rogers, M., 2014. How resource scarcity is driving the third Industrial Revolution. Available at: http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/how-resource-scarcity-is-driving-the-third-industrial-revolution.

Heuer, S., 2015. Digitalisierung als Fluch oder Segen? Oder beides? *Bertelsmann Institut*. Available at: https://www.bertelsmann-stiftung.de/de/themen/aktuelle-meldungen/2015/maerz/megatrend-digitalisierung/ [Accessed November 11, 2016].

Horx, M., 2015. Die Macht der Megatrends: Wie die großen Wandlungskräfte unsere Welt verändern. *Zukunftsinstitut*. Available at: http://www.horx.com/Reden/Macht-der-Megatrends.aspx.

Iansiti, M. & Lakhani, K. R., 2014. Digital Ubiquity: How Connections, Sensors, and Data Are Revolutionizing Business. *Harvard Business Review*, p.33. Available at: https://hbr.org/2014/11/digital-ubiquity-how-connections-sensors-and-data-are-revolutionizing-business?cm_sp=Article-_-Links-_-Top of Page Recirculation [Accessed November 22, 2016].

IDC, 2015. IDC Studie zu Industrie 4 . 0 : Maschinen- und Anlagenbauer lassen Fertigungsbetriebe weit hinter sich , Handlungsdruck zur Digitalisierung wird weiterhin unterschätzt. , pp.1–7.

Kagermann, H., Lukas, W.-D. & Wahlster, W., 2011. Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution. *VDI Nachrichten*. Available at: http://www.wolfgang-wahlster.de/wordpress/wp-content/uploads/Industrie_4_0_Mit_dem_Internet_der_Dinge_auf_dem_Weg_zur_vierten_industriellen_Revolution_2.pdf [Accessed March 3, 2016].

Kagermann, H., Lukas, W. & Wahlster, W., 2016. Abschotten ist keine Alternative. *VDI Nachrichten*, (16).

Koch, V. et al., 2014. Chancen und Herausforderungen der vierten industriellen Revolution. *Pwc*, pp.3, 4, 6, 7, 9, 11, 15–17, 33, 36–37. Available at: http://www.strategyand.pwc.com/media/file/Industrie-4-0.pdf.

Krautkraemer, J. A., 2005. Economics of Natural Resource Scarcity: The State of the Debate. *Resources for the Future*, (05–14), p.1,4,5. Available at: http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-05-14.pdf.

Lee, J., Kao, H. A. & Yang, S., 2014. Service Innovation and Smart Analytics for Industry 4.0 and Big Data Environment. *Procedia CIRP*, 16, pp.3–8. Available at: http://dx.doi.org/10.1016/j.procir.2014.02.001.

Lichtblau, D. K. et al., 2014. Industry 4.0 Readiness. , pp.0–76.

Lieder, M. & Rashid, A., 2015. Towards Circular Economy Implementation: A Comprehensive Review in Context of Manufacturing Industry. *Journal of Cleaner Production*, 115, pp.36–51.

Mani, M., Lyons, K.W. & Gupta, S.K., 2014. Sustainability Characterization for Additive Manufacturing. *Journal of Research of the National Institute of Standards and Technology*, 119, pp.419–428. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84910010994&partnerID=40&md5=f81c30f335da331d1eaafe2059f8f3f1.

McKinsey, 2015. Industry 4.0 - How to Navigate Digitization of the Manufacturing Sector. , pp.22–29, 35–37, 50.

McKinsey Stifterverband für die Deutsche Wissenschaft e.V., 2016. Hochschul-Bildungsreport 2020: Hochschulbildung für die Arbeitswelt 4.0. , p.7.

Messe München GmbH, 2015. Mechanical Engineering Underestimates Business Model Revolution. *automatica-munich.com*. Available at: http://www.automatica-munich.com/en/Home/hd/newsletter-03-16/business-model-industry-40 [Accessed November 22, 2016].

Monostori, L., 2014. Cyber-Physical Production Systems: Roots, Expectations and R&D Challenges. *Procedia CIRP*, 17, pp.9–13. Available at: http://dx.doi.org/10.1016/j.procir.2014.03.115.

Nanry, J., Narayanan, S. & Rassey, L., 2015. Digitizing the Value Chain. *McKinsey Quaterly*. Available at: http://www.mckinsey.com/business-functions/operations/our-insights/digitizing-the-value-chain.

Preston, M. & Herron, J.P., 2016. Minerals and metals scarcity in manufacturing: The ticking time bomb. *PwC*. Available at: http://www.pwc.com/gx/en/services/sustainability/publications/metal-minerals-scarcity.html.

Radziwon, A. et al., 2014. The Smart Factory: Exploring Adaptive and Flexible Manufacturing Solutions. *Procedia Engineering*, 69, pp.1184–1190. Available at: http://dx.doi.org/10.1016/j.proeng.2014.03.108.

Rasch, M. & Fischer, D., 2016. Smart Factory setzt sich in Deutschland nur langsam durch. *PwC*. Available at: http://www.pwc.de/de/digitale-transformation/smart-factory-setzt-sich-in-deutschland-nur-langsam-durch.html [Accessed November 11, 2016].

Rüßmann, M. et al., 2015. Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. *bdg.perspectives*. Available at: https://www.bcgperspectives.com/content/articles/engineered_products_project_business_industry_40_future_productivity_growth_manufacturing_industries/.

Sauter, R.D., Bode, M.D. & Kittelberger, D., 2015. *How Industry 4.0 Is Changing How We Manage Value Creation*,

Schaltegger, S. & Wagner, M., 2011. Sustainable entrepreneurship and sustainability innovation: categories and interactions. *Business Strategy and the Environment*, 20(4), pp.222–237.

Siemens, 2014a. Digital Factory Defects: A vanishing Species? Available at: http://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/digital-factories-defects-a-vanishing-species.html [Accessed April 21, 2016].

Song, Z. & Moon, Y., 2016. Assessing Sustainability Benefits of Cybermanufacturing Systems. *The International Journal of Advanced Manufacturing Technology*, pp.1–18. Available at: http://link.springer.com/10.1007/s00170-016-9428-0.

Stock, T. & Seliger, G., 2016. Opportunities of Sustainable Manufacturing in Industry 4.0. *Procedia CIRP*, 40, pp.536–541. Available at: http://www.sciencedirect.com/science/article/pii/S221282711600144X.

Sundmaeker, H. et al., 2010. Vision and Challenges for Realising the Internet of Things. , p.56.

Thrasher, J., 2014. A Primer On The Internet of Things & RFID. *RFIDinsider*. Available at: http://blog.atlasrfidstore.com/internet-of-things-and-rfid [Accessed April 28, 2016].

VDI/VDE & GMA, 2014. VDI/VDE-GMA-Fachbeiratssitzung 2014 zum Thema Industrie 4.0. Available at: https://www.vdi.de/technik/fachthemen/mess-und-automatisierungstechnik/artikel/vdi-vde-gma-fachbeiratssitzung-2014 / https://www.vdi.de/technik/fachthemen/mess-und-automatisierungstechnik/fachbereiche/anwendungsfelder-der-automation/gma-fa-723-geschaeftsm [Accessed July 29, 2016].

Wischmann,D.S.,Wangler,D.L.&Botthof,A.,2015.Industrie4.0-Volks- und betriebswirtschaftliche Faktoren für den Standort Deutschland - Eine Studie im Rahmen der Begleitforschung zum Technologieprogramm AUTONOMIK für Industrie 4.0. , pp.7, NaN, 27. Available at: https://www.bmwi.de/BMWi/Redaktion/PDF/F/industrie-4-0-volks-und_20betriebswirtschaftliche-faktoren-deutschland,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf.