A Work Project, presented as part of the requirements for the Award of a Master Degree in Management from the NOVA – School of Business and Economics.

THE IMPACT OF INDUSTRY 4.0 ON SUPPLY CHAINS

Ana Patrícia Franco Martins Lança, 3826

A Project carried out on the Master's in Management Program, under the supervision of:

Professor Manuel Pedro da Cruz Baganha

January 4th, 2018

THE IMPACT OF INDUSTRY 4.0 ON SUPPLY CHAINS

Table of Contents

Abstract

The Fourth Industrial Revolution, known as Industry 4.0 (I4.0), is fundamentally changing the way businesses operate from product development to sales. Yet, research usually focuses on its impact on production or logistics alone and little research has been done on how the supply chains (SC) of the future will look like.

In this work project, an analysis of the impact of I4.0 on SC was developed from the review of published literature, with the inclusion of small case studies that served as concrete examples of this impact. From this, a vision for the future of SC was developed.

Keywords: Industry 4.0, Smart Factory, Internet of Things, Supply chain management

I. Introduction

The world is witnessing its Fourth Industrial Revolution. Industry 4.0, as it is known across Europe, particularly in Germany, is fundamentally changing the way businesses operate (Davies, 2015; Schlaepfer, Koch, and Merkofer, 2015). Driven by the exponential development of information and communication technologies (ICT) (Xu, Xu, and Li, 2018), I4.0 is characterized by a blurring of the physical and virtual worlds (Ibarra, Ganzarain, and Igartua, 2018; Pereira and Romero, 2017). Unlike previous revolutions, which had their biggest impact on the productivity of the shop floor, at least in some industries, the biggest gains from I4.0 are expected to happen outside of production (Kautzsch, Krenz, and Sitte, 2016). I4.0 has, indeed, started in manufacturing, but it is expected to extend to other industries (Tjahjono et al., 2017). Despite that, current research into I4.0 tends to focus on its implementation and impact on production or logistics alone. Little research has been done on how its full implementation within and across company boundaries might change SC. How will interactions between organizations change? Where will the biggest benefits from I4.0 come from? How will the flow of products and information in SC look like? This work project aims to provide answers to these and other questions. In the following section, an overview of the previous Industrial Revolutions will be provided in order to establish I4.0 as a new development. After that, the methodology used to conduct the literature review this work project is based on is presented. The work project topics are, then, developed in sections IV-VIII. Section IV provides a characterization of I4.0 and a description of its key technologies. In Section V, today’s most relevant SC management challenges and frameworks are described as they will be the stepping stones for I4.0. The impact of Industry 4.0 on SC is assessed in Section VI, which includes case studies that serve as concrete examples of this impact. Section VII presents the biggest challenges SC will face in the road to the full-fledged implementation of I4.0. In Section VIII, a vision for the future of SC is provided. The work project is concluded in Section IX.

II. Background

The First Industrial Revolution started in Great Britain, in the 18th century, and was characterized by the mechanization of production (Morrar, Arman, and Mousa, 2017). The substitution of manual labor by mechanical labor, powered by water and steam, lead to a high increase in productivity in the shop floor (Geissbauer, Khurana, and Arora, 2016). A century later, between the end of the 19th century and 1914, new sources of energy - electricity and combustion - allowed for mass production based on the division of labor (Geissbauer, Khurana, and Arora, 2016; Kautzsch, Krenz, and Sitte, 2016) while technological advancements such as the telephone made communications easier (Morrar, Arman, and Mousa, 2017; Pereira and Romero, 2017). This was called the Second Industrial Revolution. With the Third Industrial Revolution, in the 1970s, came automation (Zhou, 2015). Electronics and information technologies (IT) enabled the programming and networking of machines to make production and communication even more streamlined (Geissbauer, Khurana, and Arora, 2016; Barreto, Amaral, and Pereira, 2017). Some of the most relevant technological advancements of this revolution were the programmable logic controller (PLC) and the Internet (Kautzsch, Krenz, and Sitte, 2016; Morrar, Arman, and Mousa, 2017).

Brought about by the further development of ICT, "Industrie 4.0" as a new concept first appeared at the Hannover Fair, in Germany, in 2011, and it refers to the Fourth Industrial Revolution. In 2013, it was announced as an official initiative of the German government (Wahlster et al., 2013), meant to encourage the digital transformation of Germany's strong manufacturing sector, and increase its competitiveness in the global market (Davies, 2015). Several socio-economic drivers contributed to the creation of this initiative like the movement of manufacturing jobs away from Germany due to the lower cost of labor in other parts of the world and the changing demographics that were leading to labor shortages (Koch, Merkofer, and Schlaepfer, 2015; Qin, Liu, and Grosvenor, 2016). Although, much like the Third Industrial Revolution, I4.0 has an automation component, I4.0 has a higher focus on system integration (Xu, Xu, and Li, 2018) as a means of increasing productivity, reliability and transparency of SC and of reducing costs.

Around the world, similar concepts have since emerged under other terminologies such as: "Industrial Internet of Things", "Smart Factory" and "Advanced Manufacturing" all of which are used to describe the digital transformation happening in organizations (Davies, 2015).

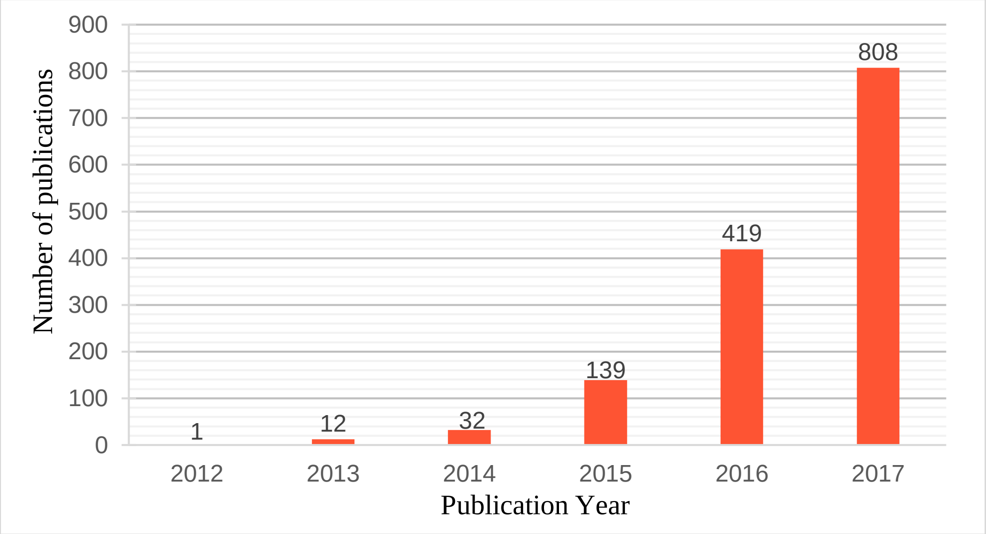
III. Methodology

A characterization of I4.0 and analysis of its impact on SC were developed based on a review of reports published by renowned consulting firms, of articles and proceeding papers indexed in the databases *B-On*, *Science Direct*, *SpringerLink*, *Emerald Insight*, *SCOPUS* and *Web of Science*, of *World Economic Forum* white papers and of European Commission and European Parliament briefings and reports. The keywords used in the research phase belonged to 3 categories: 1) “Industry 4.0”, its synonyms, and similar concepts (e.g. “Smart Factory”), 2) “Supply Chain” and related concepts (e.g. “manufacturing” and “logistics”) and 3) Key technologies associated with I4.0 (e.g. “Big Data”). The keywords in these categories were combined using Boolean operators. To validate whether the contents of the documents were in line with the objectives of this work, all introductions, in the case of reports, briefings, and white papers, or abstracts, in the case of articles and proceeding papers, were analyzed. In the last stage of document selection, the full text of each document was analyzed. Documents were excluded if the full text wasn’t available or if it was not in English. Documents were included in this review even if: they delved into technological and technical details, so long as they discussed I4.0 characteristics, benefits or challenges in a business context; I4.0 wasn’t mentioned directly, for example, in the case of documents pertaining to digital SC. In total, the content of 70 documents was analyzed at this stage. The case studies provided as examples of the impact of I4.0 on SC were obtained through this literature review and through the companies’ websites and online resources.

IV. What is Industry 4.0?

There has been an increased interest in the topic of I4.0 in academia and industry since the term was first used in 2011, observable in the increasing number of publications (Figure 1).

Figure 1 – Number of publications per year with "Industry 4.0" as a topic on the Web of Science database



However, as a new concept, "Industry 4.0" still lacks a clear, generally accepted definition. Surveys done to companies have shown that, indeed, there is a lack of understanding of what I4.0 entails in practice. Deloitte (Hochmuth, Bartodziej, and Schwägler, 2017), for instance, has used the term to mean the application of Internet of Things (IoT) to industrial processes while others define the term more broadly, referring to IoT as only one of the several technologies or concepts of I4.0 (Vaidya, Ambad, and Bhosle, 2018; Hofmann and Rüsch, 2017; Strandhagen et al., 2017). Nevertheless, many of the same technologies and concepts are mentioned in the published literature regardless of the definition used by the authors. This prevalent reference to the same key technologies reinforces the close relationship that exists between their development and this new Revolution. Industrial Revolutions have always had a strong technological driver and this one is no different (Kautzsch, Krenz, and Sitte, 2016). There are over 60 technologies associated with I4.0 (Szozda, 2017). Six key technologies were identified as its main technological drivers. A brief description of these technologies and their roles in I4.0 is presented below. It should be noted that, more than the technologies used and their development, the Industrial Revolutions are characterized by the impact the leveraging of these technologies has in the way business is conducted and, even beyond that, on the overall improvement of people's quality of life.

- *Additive Manufacturing:* Additive Manufacturing, often referred to as 3D printing, encompasses a set of manufacturing processes where three-dimensional objects are created by the successive addition of layers of material (Dolgui, Ivanov, and Sokolov, 2018). These technologies will be used in I4.0 to create individualized product offers and enable mass customization (Strandhagen et al., 2017), especially in the case of complex designs, with reduction of the number of production steps (Strange and Zucchella, 2017). Products with complex designs made with additive manufacturing can be stronger and more lightweight (Stock and Seliger, 2016a). This offers advantages such as reductions in fuel cost, in the aircraft industry. Production can also be moved closer to the customer, reducing lead times and transportation costs (World Economic Forum, 2017).
- *Augmented Reality (AR) and Virtual Reality (VR):* AR and VR are based on similar technologies but, while VR immerses the user in a completely computer-generated environment, AR overlays computer-generated objects in the real world (Nunes, Pereira, and Alves, 2017). The combination of realities in AR is valuable in processes from production support, by informing workers on which parts to use and how to use them, to quality assurance, by allowing them to compare the virtual model to the real product, to helping them pick parts in a warehouse (Vaidya, Ambad, and Bhosle, 2018). VR is most adequate to perform scenario planning. Customer data can be acquired during the product development phase by creating virtual scenarios where people might use the product to see how they use it. Production lines can be tested before they're ever put in place (Brunelli et al., 2017). Workers can be trained in virtual models of the factories, warehouses or retail stores so that the real resources remain available and that the consequences of their mistakes are minimized.
- *Big Data and Analytics:* Data is being generated at a pace higher than ever before. In

organizations, this data is collected from several sources (production and usage data from sensors in machines and products, customer data from online and offline orders, engagement data from the company's website and social media) and can't be processed using the traditional statistical methods due to the high volumes of data and variety of data formats generated, and the velocity at which it is generated (Witkowski, 2017). To deal with these new challenges, new analytical methods have been developed, enabling more informed and automated decision-making in real-time (Vaidya, Ambad, and Bhosle, 2018; Brunelli et al., 2017). This will have a significant impact on the flexibility and efficiency of the SC and on its ability to provide new and innovative offerings.

- *Cloud Computing:* Cloud computing refers to the use of remote IT infrastructures to store, manage and process data (Zhou, 2015). This technology offers high performance at a low cost (Xu, Xu, and Li, 2018) and it will be particularly important in the integration across the different players of the SC. Companies and departments within companies will be able to share data and communicate in real-time no matter where in the world they are (Khan and Turowski, 2016), with reaction times in the milliseconds (Vaidya, Ambad, and Bhosle, 2018). Moreover, this will free memory space of local devices to be used in more important tasks.
- *Autonomous Robots:* As technological developments continue, robots are becoming capable of performing ever more complex and flexible tasks with minimal or even without human intervention, at lower costs (Fitzgerald and Quasney, 2017; Strange and Zucchella, 2017). Where before, robots were programmed in rigid sets of instructions, in I4.0, they will adapt their behavior to suit the context, making use of artificial intelligence algorithms capable of endowing machines with cognitive abilities (Brunelli et al., 2017). They will become responsible for all routine operations in SC, leaving strategic and creative work to human workers. They will, in fact, work collaboratively with each other and with human workers. If a robot encounters a problem it can't solve, it will communicate with a human worker. This will bring benefits in the form of greater

flexibility in the SC, as robots will be able to switch between configurations without needing human intervention. It will also increase the speed and accuracy with which operations are performed, increase worker safety by performing tasks the dangerous that were previously done by human workers and reduce the costs of labor and of reworking defects (Fitzgerald and Quasney, 2017).

- *Internet of Things (IoT):* IoT is traditionally used to refer to a network of objects uniquely identifiable using identification technologies like Radio-frequency Identification (RFID) which are connected to the Internet and which can communicate with each other through specific protocols (Vaidya, Ambad, and Bhosle, 2018; Zhou, 2015). Objects in IoT can be machines, systems, products or even people and services. Virtual services converge to the "Internet of Services", opening up new ways of creating services and data for customers before and after purchase. Users can access information stored about the objects' provenance, state and destination in real-time using IoT technologies (Xu, Xu, and Li, 2018). In the context of I4.0, IoT will be essential for the integration of the SC and for product life cycle management, with a consequent increase in transparency and efficiency. The connectivity and interaction of Things enable the creation of services of added-value to the customer, which is one of the strongest propellers of the upcoming Revolution, unlocking a world of opportunities and challenges.

All these technologies, integrated into the Smart Factory, will lead to a growing integration of data across the product lifecycle, from product planning, development and engineering to manufacturing and sales, allowing the fusion of physical reality with computing infrastructures and automated communication. Another key component of I4.0 emerges from this – Cyber-Physical Systems (CPS). In fact, the latest literature often refers to I4.0 as a blurring of the physical and virtual worlds into CPS (Ibarra, Ganzarain, and Igartua, 2018; Pereira and Romero, 2017). CPS are physical items with computing power and data storage capabilities (Hochmuth, Bartodziej, and Schwägler, 2017; Bechtold et al., 2014). According to Lee et al. (2015), a CPS contains two components: advanced connectivity, allowing it to acquire data in real-time from the physical world and feedback from the cyber world, and an intelligent data management, analytics and computational component which models the cyber world. The true value of CPS in SC will come from the networking of these devices using the IoT. While, today, devices have very limited intelligence and the processing of data collected by sensors is typically done by feeding that data to a centralized system with better capabilities, devices in I4.0 will have embedded computing and will be able to communicate with each other and with human operators. (Rüßmann et al., 2015). The application of CPS to production, called Cyber-Physical Production Systems (CPPS), is the basis for the construction of Smart Factories (Bechtold et al., 2014). In a Smart Factory, networked machines can autonomously control production and work together in creating the product. Information about stock and demand levels, product quality, and production conditions is shared and processed in real-time (Koch, Merkofer, and Schlaepfer, 2015). Instead of being programmed to perform tasks in specific steps (e.g. programmed arm movements), machines know the tasks they must perform and work on how to best achieve desired results (Rüßmann et al., 2015).

The products created in Smart Factories can themselves be CPS, in which case they're called Smart Products (Bechtold et al., 2014). These products collect information about their use (e.g. when, how and where they were used), about their users (e.g. age and interests) and about their environment (e.g. temperature and humidity) (Nunes, Pereira, and Alves, 2017) which helps create additional value for customers and for producers. The product offering itself can be enhanced (e.g. a smart pillow that senses the person's movement and is programmed to wake them up when a certain activity level is reached can get even better with the data it collects over time) or additional Smart Services can be offered based on the data collected from the product (e.g. after-sales maintenance services can be offered when the product is malfunctioning even before the customer realizes the problem exists). Furthermore, these products will be integrated with their whole value chain with IoT and will control their own production by informing the Smart Factory of the next steps in their production (Pereira and Romero, 2017; Rüßmann et al., 2015). This also means that they can be located at any time during their life cycle (Erol et al., 2016).

But an I4.0 means integration even beyond the company-wide networking of machines and products. Three integration dimensions are identified in literature:

1. *Horizontal integration* across IT systems, processes and resources of all the participants of the value chain including customers and business partners across the globe (Schumacher, Erol, and Sihn, 2016; Koch, Merkofer, and Schlaepfer, 2015);
2. *End-to-end engineering* across the entire product life cycle from raw material acquisition, manufacturing and product use to the product end-of-life (Stock and Seliger, 2016b);
3. *Vertical integration* along the company's own departments and hierarchical levels such as procurement, manufacturing, distribution, marketing and sales (Strandhagen et al., 2017).

Physical flows of parts and products will be mapped across the network of integrated SC players in these three dimensions with identification and location technologies while IoT and cloud technologies will be essential for the seamless flow of information. Above all, it is this integration of IT systems, networks and physical processes that characterizes I4.0. The seamless integration will enable SC to overcome their current struggles and increase their efficiency beyond the marginal gains that today's processes and technologies can offer them. The extent to which it will happen will depend on the speed and extent of development of the technologies that support it which is dependent on the embracing of the inherent innovations by society (institutions and ordinary citizens) and the recognition of their long-term benefits (Schwab, 2017).

V. Today's supply chains

Ganeshan and Harrison (1995) define "supply chain" as a "network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers." Traditionally these facilities are geographically dispersed and are operated by various organizations which act independently, often with conflicting interests (Büyüközkan and Göçer, 2018). Still, organizations in the SC must find the answers to questions such as "What product does the market want and how much of it does it want?" and "How should inventory be moved between facilities?". The concept of supply chain management appears in the late 1980s and its aim is to obtain answers these questions such that the SC achieves higher efficiency levels while maintaining short lead times and smooth flow of information and materials (Ganji, Coutroubis, and Shah, 2018; Hugos, 2003). Some of the now most widely used supply chain management terms were also popularized in the late 1980s and 1990s such as "Lean Manufacturing" and "Just-in-time" (Ganji, Coutroubis, and Shah, 2018). Lean Manufacturing is now a standard throughout the industry, being implemented in 90% of manufacturing companies (Dombrowski, Richter, and Krenkel, 2017). Many of the concepts of Lean are useful for the adoption of I4.0 such as "failing fast" and the creation of integrated teams. In fact, Boston Consulting Group studies (Küpper et al., 2017) show that companies should implement both Lean and I4.0 holistically in what they call "Lean Industry 4.0" if they want to attain the highest levels of operational efficiency. This is not a new concept entirely, as the attempts to integrate Lean Manufacturing and automation, termed "Lean Automation", began in the 1990s (Kolberg and Zühlke, 2015). However, Lean Automation didn't take the new ICT developments into account. As such, the integration of Lean Manufacturing and I4.0 has been a research topic of interest (Kolberg and Zühlke, 2015; Küpper et al., 2017; Mrugalska and Wyrwicka, 2017). The implementation of these frameworks will enable companies to better face their current SC problems and changing market needs, namely:

- *Increasing global competition*: Companies now compete on a global level, where products and prices can be compared with increased ease as information becomes more readily available to consumers (Bär, Herbert-Hansen, and Khalid, 2018), which decreases their margins (Deloitte, 2017; Rojko, 2017).

- *Market volatility*: SC need to have enough flexibility to be able to respond to unpredictable changes in demand, which are happening ever more frequently (Deloitte, 2017; Morrar, Arman, and Mousa, 2017).
- *Demand for highly individualized products:* The demand for customized products and services is growing. Companies are required to evolve from mass production to personalization and customization to meet customer needs (Bär, Herbert-Hansen, and Khalid, 2018). With traditional production methods, responding to the requirement of customer customization is too costly and time-consuming, so profound change is needed (Alicke, Rachor, and Seyfert, 2016).
- *Shortened product life cycles:* The pace of development of the modern economy means that companies are forced to constantly introduce more and more new solutions. With the constant pressure of launching novelties and innovations into the current market, the product life cycle becomes shorter and shorter, making products obsolete quickly (Hofmann and Rüsch, 2017; Morrar, Arman, and Mousa, 2017).
- *Ripple chain effect and ineffective SC risk management*: The existence of several layers of stakeholders increases the variability risks for SC (Deloitte, 2017).
- *Lack of end-to-end SC visibility*: With the increasing SC complexity, companies are struggling to have a clear overview of their SC. This creates problems of traceability such as failure to identify the sources of issues that arise (Deloitte, 2017).

Slow response to market demands and the lack of efficient SC can lead to huge financial losses. Thus, one of the primary goals of any company will certainly be to eliminate the inefficiencies that exist throughout its SC and increase its reactivity to the current market changes. In a market that is increasingly global, where consumers have a wide variety of choices, the need for an efficient and resilient SC sometimes means more than a gain in competitiveness, it is a question of survival.

VI. Impact of Industry 4.0 on supply chains

We are living in a state of global economy, integration and partnership. Yet, in industry, integration is still very limited. Few companies are fully connected to their suppliers and customers. Adapting the SC to this environment using emerging technologies and processes is a challenge that will require a new kind of organizational effort. SC that successfully adapt will see their efforts translated into a high number of opportunities for growth.

- *Increased flexibility and mass customization:* To meet the changing consumer expectations and needs for more individualized products, and the irregular demand fluctuations, SC must gain flexibility (Hecklau et al., 2016). This flexibility will be acquired, on one hand, through the processing of Big Data for the dynamic selection of production facilities, suppliers, distributors and other service providers for each production job considering real-time changes in demand, resource condition and availability, and pre-defined criteria (e.g. shortest lead time or cheapest option) (Alicke, Rachor, and Seyfert, 2016; Bechtold et al., 2014). For instance, information about the weather and traffic can be used to adjust self-driving truck routes (Hofmann and Rüsch, 2017). DHL's "Resilience360" platform uses Big Data technologies to manage SC risk. The platform maps the SC end-to-end and monitors risk in several categories across the globe. When events happen that might disrupt the SC, the platform notifies companies so that they can try to mitigate the arising disruption (Dolgui, Ivanov, and Sokolov, 2018; DHL International GmbH, 2018; Witkowski, 2017). Prices can also be dynamically adjusted based on information about demand and available capacity (Alicke, Rachor, and Seyfert, 2016). Pharmapacks, a health and beauty online marketplace, created a software that updates their prices every 45 minutes. The software tries to set the lowest prices for their products that are still profitable for them, as part of their selling strategy (Dolgui, Ivanov, and Sokolov, 2018). On the other hand, manufacturers will also have more flexible production lines. A flexible production line can make multiple products. This usually implies high costs as time-consuming changeovers are required so that machinery can be prepared to produce new products but that will not be the case in I4.0. The use of autonomous and self-configuring machines connected through the IoT will enable cooperative adaptation to the new production processes. Machines equipped with sensors will be able to read the RFID tags on products, know which manufacturing steps must be performed and adjust their parameters or tools accordingly (Rüßmann et al., 2015). This will enable mass customization, which combines the benefits of customization and mass production, meeting customer needs more precisely by altering the product to meet individual needs but remaining fast and feasible cost-wise (Zawadzki and Zywicki, 2016). Bosch Rexroth's Multi Product Line is an application of this. The line was first installed at their Homburg plant in Germany to produce electro-hydraulic valves of 6 basic types in 200 versions (Bosch Rexroth AG, 2016; Rüßmann et al., 2015). The trend of customization means more than simply developing and producing different versions of the product to meet different customer segments or individuals and goes on to include the customer in the design process in what is called "collaborative customization" (Zawadzki and Zywicki, 2016). In this type of customization, companies typically provide software platforms in which customers can customize products by choosing between parameters for a limited set of product characteristics (Zawadzki and Zywicki, 2016). It can also enable a higher freedom in the creation of product variants, with the addition of new product characteristics by the customer or even with the submission of their own designs. Shapeways, a Dutch start-up, offers its 3D printing services on its website where customers can upload their own 3D models to be manufactured in a variety of materials, in batches as small as a single unit. Because the software can determine how to 3D print the design using the machines' functionalities, each order can be unique (Shapeways, 2018).

- *Increased product quality:* Smart machines in I4.0 can have sensors that analyze the quality of each product as it is being produced, which eliminates the need to collect samples and perform statistical analysis. Since information about machines and products is collected and processed in real-time, it is possible to more quickly identify and correct problems arising in production or logistics that might be affecting product quality. For instance, a machine or truck might be registering higher temperatures than normal. In that case, it might try to self-correct or it might send a warning to a worker's wearable. In production, the use of technologies such as AR will help operators in choosing the right parts to use in production for each step as well as show them the correct way of proceeding, thus, reducing operator error. Airbus employees on the shop floor use a hand-held device that displays a 3D model on top of the real aircraft, that can help them determine the size and positioning of parts (AIRBUS, 2018). That information can be shared with robots so that they can assist in completing the tasks (Bonneau et al., 2017). Operator information collected by the workers wearables will also be stored which will help guarantee that only authorized operators handle the equipment and the products, making quality checks and audits easier and assuring operator safety, especially in industries with very tight quality regulations like the aircraft (Bonneau et al., 2017) or the pharmaceutical industries. This information will be stored in the cloud alongside all other product data collected as it moves within the SC (e.g. date of order shipment to the customer), improving SC transparency and making it easier to trace quality problems back to their source. McLaren Racing, a Formula One team, uses RFID chips in all their car parts so that all material flow is tracked throughout the SC. This enables them to identify the supplier of the metal used to produce a certain part or know when it was inspected, and guarantee the quality of their product (Deloitte Insights, 2018). The overall rise in quality means that less rework will be needed and fewer pieces will be scrapped. A Siemens smart factory in Amberg, Germany, that produces PLC now records 12 defects per million (Davies, 2015). It is estimated that if all defects were eliminated, European manufacturers would save approximately 160 billion euros (Davies, 2015).

- *Increased speed***:** During product development, fewer physical prototypes will be created (Rüßmann et al., 2015). Instead, AR and VR will be used to generate designs (Accenture, 2015), simulate the product and get insight into how costumers might use it. Additive manufacturing will be used for quick and inexpensive prototyping when a physical copy of the product is needed. This can greatly reduce the time taken to design a product, getting it to the market faster (Nunes, Pereira, and Alves, 2017; Davies, 2015). In production, simulations will be used to test production lines before their implementation, which can reduce setup times and downtimes while also reducing start-up errors (Vaidya, Ambad, and Bhosle, 2018). In conjunction with a German machine-tool vendor, Siemens developed a virtual machine that can simulate machine parts from the data collected by the physical machines. This process can lower setup times by up to 80% (Rüßmann et al., 2015). In working production lines, defects can be more easily and swiftly detected using sensors and AR. Workers using AR glasses can compare the physical products with their virtual representations of the desired finished product. This type of inspection has resulted in the reduction of inspection times of brackets on Airbus A380 fuselage from three weeks to three days (AIRBUS, 2018). Meanwhile, new production methods such as Additive Manufacturing, will also have an impact on the lead times of SC by simplifying the production of complex designs, and bringing production closer to the customer and eliminating intermediate transportation of goods (Strange and Zucchella, 2017; Bechtold et al., 2014). Moving production is possible because the utilization of I4.0 technologies reduces the amount of human labor needed and, therefore, the cost of labor becomes less important in the selection of plant locations. The introduction of Additive Manufacturing to Adidas' production process in its new Adidas Speedfactory, in Germany, reduced the time needed to have a finished pair of sneakers in the country of destination from three months to five hours by avoiding transportation from Asian countries (Dolgui, Ivanov, and Sokolov, 2018).

- *Increased productivity*: Much like all other industrial revolutions, I4.0 will result in productivity gains. Smart Factories capable of predictive maintenance will be able to reduce downtimes caused by machine failure, which cost industrial manufacturers billions of euros each year (Fitzgerald and Quasney, 2017). Maintenance will be performed at the optimal time (Küpper et al., 2017). This will replace having to either run machines until failure, which can cause serious accidents, or having to replace parts regularly, throwing away functioning parts too early, both of which would increase maintenance costs (Fitzgerald and Quasney, 2017). This is estimated to increase production by 20% (Davies, 2015). Predictive maintenance is utilized by Thames Water, the largest water supply and waste-water treatment company in the United Kingdom, which uses sensors and Big Data analytics to anticipate equipment failures in their trunk mains (Thames Water, 2017). The integration of Smart Factories will allow for better capacity utilization (Bechtold et al., 2014) and for the optimization of business processes as information collected from each factory is compared to the others, so that if it is doing better than the others, the processes utilized there can be applied company-wide (Khan and Turowski, 2016). These factories may be able to work in the absence of human workers for long periods of time, in what are called "lights out" factories, which get their name from the fact that they can operate without the need for conditions that make it possible and comfortable for humans to work there, such as lighting. The robots in these factories can work without breaks, unlike humans. In one FANUC factory, in Japan, robots replicate themselves in the absence of lighting, heat and air conditioning, with a production capacity of 5000 ROBOTs a month (FANUC CORPORATION, 2018; Wheeler, 2015).
- *New business models:* More than simply allowing for process optimization and cost reduction, I4.0 allows companies to develop entirely new business models. This can be the creation of innovative products and services but also of pricing models. The easiest step for companies will be to offer services alongside its existing products, which creates a source of recurring revenue, for

example, in the form of a monthly subscription to an associated service (Bonneau et al., 2017; Bornstein, Brooke, and Wyk, 2018). This is the "product-as-a-service" business model. One example of the application of this is the TotalCare® service provided by Rolls-Royce, which offers engine maintenance to its customers, based on the collection and analysis of engine performance data. This service is charged on a fixed fee per flying hour basis and constitutes a source of revenue 4 times higher than the product cost (Bonneau et al., 2017; Rolls-Royce, 2017). Companies can also charge for different levels of access to data and services (Bornstein, Brooke, and Wyk, 2018). The lower level could offer customers simple logs or basic reports of the data collected by the products while upper tiers would provide them with additional insights into the data and add services such as predictive maintenance or suggestions on how to better utilize the products. Atlas Copco, a Swedish industrial equipment and tools manufacturer, provides tiered access to data in its SMARTLINK offering, aimed at helping customers monitor their compressed air installations. The lower tiers give customers access to service logs, notification services and the ability to more easily get quotes for parts and services while the upper tier provides customers with more detailed reports on the energy efficiency of their compressor rooms (Bornstein, Brooke, and Wyk, 2018). Other associated services can come in the form of product software updates to improve usage conditions (e.g. the minimization of energy consumption) or the automated ordering of replacement parts (Bechtold et al., 2014; Ibarra, Ganzarain, and Igartua, 2018). A very well-known example of the usage of product software updates is the case of Tesla cars which *"receive over-the-air software updates that add new features and enhance existing functionality via Wi-Fi"* (Tesla, 2018).

As companies develop their digital capabilities, they may also create new value propositions not intrinsically linked to their core product. For example, companies might sell consulting services based on the insights they've acquired from the processing of customer-collected data or they might make their digital platforms available to third-parties (Kautzsch, Krenz, and Sitte, 2016).

VII. Challenges

Applications of I4.0 technologies and processes have started to emerge, and have been previously mentioned, but the greatest impact of the so-called I4.0 is still to come, not only in work-related aspects but also socially. Which challenges do companies face moving forward, given the new level of complexity and interconnectivity that comes with I4.0?

- *Technological development:* As previously mentioned, the expansion of I4.0 is tightly linked to the development of its key technologies. Albeit many of them have been around for 20 or 30 years, they are only now reaching desired performance levels at affordable prices for companies (Dombrowski, Richter, and Krenkel, 2017; Koch, Merkofer, and Schlaepfer, 2015). However, even today, significant development is still needed before they become capable of performing as required for companies to reap the full benefits of I4.0. Most technologies associated with I4.0 such as "Cognitive Computing", "Smart Robots", "IoT platform" and “Autonomous Vehicles” are on Gartner's 2017 peak of inflated expectations (Panetta, 2017). It is yet to be seen how much of what is said about the future performance of these technologies is going to be a reality in the next few years. Companies will need to pay close attention to technological developments but will generally not develop this technology in-house and will need to partner with universities, technology companies and infrastructure providers (Davies, 2015). They may also acquire start-ups.
- *High investment:* I4.0’s promises of high revenue gains will come with significant investments from companies. In a recent study, PricewaterhouseCoopers (Geissbauer et al., 2014) estimated that European industrial companies will invest 140 billion euros annually in Industrial Internet applications by 2020. Companies will need to invest in the retrofitting of their existing equipment (Accenture, 2015) as well as in new equipment such as costly digital infrastructures to be able to store, transfer and process all the data captured in I4.0 (Bechtold et al., 2014). This will especially be a challenge for small and medium-sized enterprises (SME) and will require government

intervention as SME employ a high percentage of the world's population and are responsible for much of the economic growth (World Economic Forum, 2017).

- *Workforce skills:* I4.0 will require a workforce with new capabilities (Bechtold et al., 2014). Lower skilled jobs will disappear as automation increases (Davies, 2015). Instead, workers will work alongside I4.0 technologies in new jobs that will be created (Accenture, 2015). Companies will need to rethink their recruiting and training. Human workers will need to be able to react swiftly to actions prompted by machines (Accenture, 2015) but they will also need to be trained so that they will think critically of the results obtained by technologies and such that they will be able to perform tasks even when machines are not working, as there is a human tendency be over-reliant on machine solutions, known as "automation bias" (Deloitte Insights, 2018). Beyond upskilling and retraining their employees, companies will need to search for potential employees in new talent pools by partnering with outside organizations (Bremicker and Gates, 2017).
- *High complexity*: The increasing accessibility to sensors and Big Data analytics capabilities is enabling companies to easily capture data from many sources (Khan and Turowski, 2016). Companies must learn to deal with this complexity by standardizing and simplifying their data collection, storage and processing processes such that insights don't become obscured to the point where they're impossible to find, data storage costs don't sky-rocket and data management regulation non-compliance risks don't pile up (EY, 2016). Product and service data has to be well documented as mass customization makes it harder to determine what is being offered and how well each variation is performing (Bornstein, Brooke, and Wyk, 2018). Managing a network of smart factories and business partners will add complexity. To exchange data efficiently between the different IT infrastructures, standardized interfaces must be developed (Hecklau et al., 2016).
- *Cybersecurity*: Smart products, industrial machines and work computers can be hacked into, especially given that they traditionally aren't updated on a regular basis (Khan and Turowski,

2016). In an I4.0, where a high level of integration between SC systems is required, a security breach can more easily spread through the entire SC or even through entire industries. One example of this was an attacked denominated “WannaCry”, in 2017, which affected computers from a variety of organizations in over 150 countries running older versions of the Microsoft Windows operating system (World Economic Forum, 2017). Companies will need to invest in secure and reliable communications and data sharing platforms. With the extreme lack of workers in this area, with an unemployment rate of 0 percent, that might mean that more AI will be used to cover up this skills gap (Deloitte Insights, 2018). Cybersecurity is frequently found to be stakeholders main concern (McKinsey Digital, 2016) and this is not unfounded as the annual cost of cyberthreats today is valued in the trillions of euros and is expected to increase (Deloitte Insights, 2018).

- *Legalities /Data ownership, Intellectual Property (IP) and Worker’s rights:* There are several legal issues that need to be addressed before companies fully reap the benefits of I4.0. One of which is that of data ownership. Customers might not let the manufacturer have access to and own all the data generated by their products once they’ve bought the product (Bornstein, Brooke, and Wyk, 2018). If manufacturers have access to that data, that might change the power dynamics in the SC (Kautzsch, Krenz, and Sitte, 2016). Additionally, the sharing of data creates the risk of a company’s competitor gaining access to it. Agreements will have to be made on which data is shared and how it is shared, how it can be used, and who owns the data and the insights generated from it. This is complemented by the issues of IP. It will be important to determine who owns which rights to the product. If a customer creates the design or part of a design of a customized product, it will be important to determine which ownership the customer detains over the design. Other legal issues arise from the traceability provided by the data collection in I4.0. Data from wearables such as worker location can be useful to optimize the layout of the shop floor, but it might also be used to monitor and evaluate workers, infringing their privacy rights (Davies, 2015).

The major challenge the industry faces today is the creation of value that translates into more market share, more profit, and a stronger brand. In short, making I4.0 a tool that generates financial and competitive benefits to the business. Often, new companies are more innovative but do not have the necessary funding. It is, therefore, essential the establishment of partnerships and getting the necessary financial support. For companies already established in the market, sometimes the challenge is even greater, as there is a natural tendency to maintain their current structure, for fear of taking risks. The greatest risk always lies in not adapting to the new market. Companies must be bold in their approach to I4.0 or they will risk disappearing.

VIII. How will the supply chains of the future look like?

Future SC will be characterized by the integration of systems across networks of organizations and individuals, within and across industries. Information in the network will be captured about the physical world (e.g. product information and sensor data), will be transferred between machines and analyzed, and will result in a physical response (e.g. the turning of a robotic arm or the dispatching of a distribution drone with a customer's order). Hybrid data recording systems, i.e. the keeping of paper and digital records, will be eliminated (Bechtold et al., 2014). This is paramount in order to reap the full benefits of the integrative and analytical capabilities of I4.0. Data must be updated in real-time in the cloud in order to gain higher flexibility, efficiency and resilience through higher forecasting accuracy and traceability. This will allow companies to work with lower or even no safety stocks and have reduced lead times (Alicke, Rachor, and Seyfert, 2016; Strandhagen et al., 2017). The SC will operate on a pull basis whereby all parts and products are connected to particular orders. It might even be the case that the consumption of the product automatically informs the SC and a replenishment order is immediately placed (Hofmann and Rüsch, 2017). This might require the integration between several players (e.g. for a replenishment order to be placed for a jug of milk from a customer's house, manufacturers of smart refrigerators might partner with retailers, which might themselves partner with milk suppliers so that when the smart fridge registers the order, all these players are notified). Real-time inventory management will be possible using image-recognition AI technologies which are able to “see” which shelf space is empty or which products are on the shelf, in warehouses and retail shelves (Gesing, Peterson, and Michelsen, 2018). Changes to the state of the shelf will be automatically recorded in the cloud so that it is available to all SC players (Szozda, 2017). In Smart Factories, CPS and Augmented Workers, i.e. workers equipped with wearables which give them information on production requirements (Rüßmann et al., 2015), will work collaboratively on creating products that will more closely match customers needs. The increased customer empathy will be acquired through the collection of data by products in use (when and how it’s being used, how often, what type of use) by the customer and from the customer input during product development as the production development itself will be crowdsourced to external partners and customers in open platforms (Bechtold et al., 2014). That same data can be used to provide value-added services and to effectively market the companies’ products and services to customers. Inside the Smart Factories and warehouses, Automated Guided Vehicles (AGVs) will be in charge of the transporting of parts to workstations while autonomous robots will be in charge of unloading, stocktaking, picking, packing and shipping (Alicke, Rachor, and Seyfert, 2016). Driverless trucks and drones will handle the transportation between facilities. These Smart systems cooperate to manage capacity (Alicke, Rachor, and Seyfert, 2016) and their routes can be optimized with Big Data analytics (Hofmann and Rüsch, 2017). They will communicate their position to the network as well as their predicted arrivals times which will allow the Smart systems of Smart Factories, warehouses and retail stores to prepare docking stations and shelf spaces or start up Smart machines ahead of time (Barreto, Amaral, and Pereira, 2017). The delivery of the goods will automatically update the data on the cloud (Barreto, Amaral, and Pereira, 2017), such as stock availability, delivery time, name of the company it was delivered to and docking station identification. Customers will select the most convenient shopping channels for them and switching between them will be easy. Shopping will be done online or through a physical store and they will choose from a variety of shipping methods (Dutzler et al., 2016). It will be important for companies to keep a coherent experience across channels (Szozda, 2017) and, with seamless integration, it will be possible to keep track of customers even if they switch channels and keep the waiting times low.

IX. Conclusion & Future Work

The speed of innovation and the extent and scope of the changes that follow, is faster than ever. Many things that were previously considered science fiction have ceased to be so, as they already exist or are being developed and improved by the great economic agents. The future of industry, termed Industry 4.0, will be determined by the ability to collect all data considered relevant, process it, and transform it into valuable insights. This requires technologically advanced systems with real-time processing capabilities and sophisticated algorithms. The creation of networks of those systems, capable of cooperatively harnessing the wisdom taken from data processing and taking real action will open new horizons for SC and society. It is estimated that achieving the full potential of I4.0 might still take at least 10 to 20 years (Zawadzki and Zywicki, 2016). This will not come without challenges, however, as the integration required by I4.0 will increase the threat of cyberattacks, and the increased automation of work may lead to job losses if nothing is done. This work was limited in its scope, analyzing only what has been published in literature. Future work should, then, aim at studying the impact of I4.0 on SC applying methods such as expert interviews. This will serve to identify the gap between what is expected and what is being done in practice by companies. Future research should differ from the content of the current literature in that it should focus on answering the questions posed in the beginning of this work project, i.e. it should focus on the integration aspect and wider impact of I4.0 on SC.

X. References

Accenture. 2015. “Smart Production, Finding a Way Forward: How Manufacturers Can Make the Most of the Industrial Internet of Things.” https://www.accenture.com/_acnmedia/PDF-5/Accenture-804893-Smart-Production-POV-Final.pdf.

AIRBUS. 2018. “Virtual Reality with Real Benefits.” Accessed November 30. https://www.airbus.com/newsroom/news/en/2017/09/virtual-reality-with-benefits.html.

Alicke, Knut;, Jürgen; Rachor, and Andreas; Seyfert. 2016. “Supply Chain 4.0 - the next-Generation Digital Supply Chain,” no. June. https://www.mckinsey.com/business-functions/operations/our-insights/supply-chain-40--the-next-generation-digital-supply-chain.

Bär, Kristina, Zaza Nadja Lee Herbert-Hansen, and Waqas Khalid. 2018. “Considering Industry 4.0 Aspects in the Supply Chain for an SME.” *Production Engineering* 12 (6): 747–58. https://doi.org/10.1007/s11740-018-0851-y.

Barreto, L., A. Amaral, and T. Pereira. 2017. “Industry 4.0 Implications in Logistics: An Overview.” *Procedia Manufacturing* 13: 1245–52. https://doi.org/10.1016/j.promfg.2017.09.045.

Bechtold, Jochen, Andreas Kern, Christoph Lauenstein, and Lena Bernhofer. 2014. “Industry 4.0 - The Capgemini Consulting View.” *Capgemini Consulting*, 1–31. https://doi.org/10.1587/transcom.E94.B.2423.

Bonneau, Vincent, Bertrand Copigneaux, Bertrand Pedersen, Laurent Probst, and Olivia-Kelly Lonkeu. 2017. “Industry 4.0 in Aeronautics: IoT Applications.” https://ec.europa.eu/growth/tools-databases/dem/monitor/sites/default/files/DTM_Aeronautics - IoT Applications v1.pdf.

Bornstein, Justine, Peter Brooke, and John Van Wyk. 2018. “Selling Industry 4.0 - The New Sales Mind-Set for Connected Products.”

https://www2.deloitte.com/content/dam/insights/us/articles/4419_IoT-and-sales/DI_Selling-Industry4-0.pdf.

Bosch Rexroth AG. 2016. “Industry 4.0 - Innovations and Trends from Industry for Educational Institutes.” Accessed November 12. https://dc-us.resource.bosch.com/media/us/training_2/documents_36/R999001298_2016-4.pdf.

Bremicker, Michael, and Doug Gates. 2017. “Beyond the Hype - Separating Ambition from Reality in I4.0.” https://assets.kpmg/content/dam/kpmg/xx/pdf/2017/05/beyond-the-hype-separating-ambition-from-reality-in-i4.0.pdf.

Brunelli, Jacapo, Vladimir Lukic, Tom Milon, and Marco Tantardini. 2017. “Five Lessons from the Frontlines of Industry 4.0.” *The Boston Consulting Group*. https://www.bcg.com/publications/2017/industry-4.0-lean-manufacturing-five-lessons-frontlines.aspx.

Büyüközkan, Gülçin, and Fethullah Göçer. 2018. “Digital Supply Chain: Literature Review and a Proposed Framework for Future Research.” *Computers in Industry* 97: 157–77. https://doi.org/10.1016/j.compind.2018.02.010.

Davies, Ron. 2015. “Industry 4.0 - Digitalisation for Productivity and Growth.” *European Parliamentary Research Service*. https://doi.org/10.1016/j.csr.2008.01.002.

Deloitte. 2017. “Continuous Interconnected Supply Chain - Using Blockchain & Internet-of-Things in Supply Chain Traceability.” https://www2.deloitte.com/content/dam/Deloitte/lu/Documents/technology/lu-blockchain-internet-things-supply-chain-traceability.pdf.

Deloitte Insights. 2018. “Deloitte Review: Industry 4.0 : Are You Ready?” *Deloitte Insights*.

DHL International GmbH. 2018. “Supply Chain Risk Management Software | DHL Resilience360 DHL Resilience360.” Accessed November 12.

https://www.resilience360.dhl.com/.

Dolgui, Alexandre, Dmitry Ivanov, and Boris Sokolov. 2018. “Ripple Effect in the Supply Chain: An Analysis and Recent Literature.” *International Journal of Production Research* 56 (1–2): 414–30. https://doi.org/10.1080/00207543.2017.1387680.

Dombrowski, Uwe, Thomas Richter, and Philipp Krenkel. 2017. “Interdependencies of Industrie 4.0 & Lean Production Systems: A Use Cases Analysis.” *Procedia Manufacturing* 11 (June): 1061–68. https://doi.org/10.1016/j.promfg.2017.07.217.

Dutzler, Harald, Peter Hochrainer, Axel Nitschke, Benedikt Schmaus, and Stefan Schrauf. 2016. “Industry 4.0 - Opportunities and Challenges for Consumer Product and Retail Companies.” https://www.accenture.com/_acnmedia/PDF-5/Accenture-804893-Smart-Production-POV-Final.pdf.

Erol, Selim, Andreas Jäger, Philipp Hold, Karl Ott, and Wilfried Sihn. 2016. “Tangible Industry 4.0: A Scenario-Based Approach to Learning for the Future of Production.” *Procedia CIRP* 54: 13–18. https://doi.org/10.1016/j.procir.2016.03.162.

EY. 2016. “Digital Supply Chain: It’s All about That Data.” https://www.ey.com/Publication/vwLUAssets/Digital_supply_chain_-_its_all_about_the_data/$FILE/EY-digital-supply-chain-its-all-about-that-data-final.pdf.

FANUC CORPORATION. 2018. “Headquarter Factories - Production.” Accessed November 22. https://www.fanuc.co.jp/en/profile/production/factory1.html.

Fitzgerald, Joseph, and Evan Quasney. 2017. “Using Autonomous Robots to Drive Supply Chain Innovation.” https://www2.deloitte.com/content/dam/Deloitte/us/Documents/manufacturing/us-manufacturing-autonomous-robots-supply-chain-innovation.pdf.

Ganeshan, Ram, and Terry P. Harrison. 1995. “An Introduction to Supply Chain Management.”

1995. http://lcm.csa.iisc.ernet.in/scm/supply_chain_intro.html.

Ganji, E N, A Coutroubis, and S Shah. 2018. “DCM 4.0: Integration of Industry 4.0 and Demand Chain in Global Manufacturing.” In *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, 1–7. https://doi.org/10.1109/ICE.2018.8436383.

Geissbauer, Reinhard, Anil Khurana, and Jantin Arora. 2016. “Industry 4.0: Building the Digital Enterprise, 2016 Middle East Industry 4.0 Survey.” https://www.pwc.com/m1/en/publications/documents/middle-east-industry-4-0-survey.pdf.

Geissbauer, Reinhard, Stefan Schrauf, Volkmar Kock, and Simon Kuge. 2014. “Industry 4.0: Opportunities and Challenges of the Industrial Internet.” *PwC* 13. https://doi.org/10.1016/j.futures.2014.12.002.

Gesing, Ben, Steve J. Peterson, and Dirk Michelsen. 2018. “Artificial Intelligence in Logistics.” *DHL Customer Solutions & Innovation*. https://doi.org/10.2307/3060633.

Hecklau, Fabian, Mila Galeitzke, Sebastian Flachs, and Holger Kohl. 2016. “Holistic Approach for Human Resource Management in Industry 4.0.” *Procedia CIRP* 54: 1–6. https://doi.org/10.1016/j.procir.2016.05.102.

Hochmuth, Christian A., Christoph Bartodziej, and Carolin Schwägler. 2017. “Industry 4.0. Is Your ERP System Ready for the Digital Era?” https://www2.deloitte.com/content/dam/Deloitte/de/Documents/technology/Deloitte_ERP_Industrie-4-0_Whitepaper.pdf.

Hofmann, Erik, and Marco Rüsch. 2017. “Industry 4.0 and the Current Status as Well as Future Prospects on Logistics.” *Computers in Industry* 89: 23–34. https://doi.org/10.1016/j.compind.2017.04.002.

Hugos, M. 2003. *Essentials of Supply Chain Management*. Hoboken: John Wiley & Sons, Inc.

Ibarra, Dorleta, Jaione Ganzarain, and Juan Ignacio Igartua. 2018. “Business Model Innovation through Industry 4.0: A Review." *Procedia Manufacturing* 22: 4–10. https://doi.org/10.1016/j.promfg.2018.03.002.

Kautzsch, Thomas, Wolfgang Krenz, and Tobias Sitte. 2016. "Digital Industry - the True Value of Industry 4.0." *Oliver Wyman*, 0–24. https://www.oliverwyman.com/content/dam/oliver-wyman/global/en/2016/june/OliverWyman_Digital Industry 2016_web.pdf.

Khan, Ateeq, and Klaus Turowski. 2016. "A Survey of Current Challenges in Manufacturing Industry and Preparation for Industry 4.0." In *Proceedings Ofthe First International Scientific Conference "Intelligent Information Technologies for Industry,"* edited by A. Abraham, S. Kovalev, V. Tarassov, and V. Snášel, 15–26. Springer International Publishing Switzerland. https://doi.org/10.1007/978-3-319-33609-1_2.

Koch, Markus, Philipp Merkofer, and Ralf C. Schlaepfer. 2015. "Deloitte - Industry 4.0 Challenges and Solutions for Digital Transformation." https://www2.deloitte.com/content/dam/Deloitte/ch/Documents/manufacturing/ch-en-manufacturing-industry-4-0-24102014.pdf.

Kolberg, Dennis, and Detlef Zühlke. 2015. "Lean Automation Enabled by Industry 4.0 Technologies." *IFAC-PapersOnLine* 48 (3): 1870–75. https://doi.org/10.1016/j.ifacol.2015.06.359.

Küpper, Daniel, Ailke Heidemann, Johannes Ströhle, Daniel Spindelndreier, and Claudio Knizek. 2017. "When Lean Meets Industry 4.0." *The Boston Consulting Group*, no. 12/17: 15.

Lee, Jay, Behrad Bagheri, and Hung An Kao. 2015. "A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems." *Manufacturing Letters* 3: 18–23. https://doi.org/10.1016/j.mfglet.2014.12.001.

McKinsey Digital. 2016. "Industry 4.0 after the Initial Hype - Where Manufacturers Are Finding Value and How They Can Best Capture It."

https://www.mckinsey.com/~/media/mckinsey/business functions/mckinsey digital/our insights/getting the most out of industry 4 0/mckinsey_industry_40_2016.ashx.

Morrar, Rabeh, Husam Arman, and Saeed Mousa. 2017. “The Fourth Industrial Revolution (Industry 4.0); A Social Innovation Perspective.” *Technology Innovation Management Review* 7 (11): 12–21. https://doi.org/10.22215/timreview/1117.

Mrugalska, Beata, and Magdalena K. Wyrwicka. 2017. “Towards Lean Production in Industry 4.0.” *Procedia Engineering* 182: 466–73. https://doi.org/10.1016/j.proeng.2017.03.135.

Nunes, M. Lopes, A. C. Pereira, and A. C. Alves. 2017. “Smart Products Development Approaches for Industry 4.0.” *Procedia Manufacturing* 13: 1215–22. https://doi.org/10.1016/j.promfg.2017.09.035.

Panetta, Kasey. 2017. “Top Trends in the Gartner Hype Cycle for Emerging Technologies, 2017 - Smarter With Gartner.” Gartner. Accessed October 7. https://www.gartner.com/smarterwithgartner/top-trends-in-the-gartner-hype-cycle-for-emerging-technologies-2017/.

Pereira, A. C., and F. Romero. 2017. “A Review of the Meanings and the Implications of the Industry 4.0 Concept.” *Procedia Manufacturing* 13: 1206–14. https://doi.org/10.1016/j.promfg.2017.09.032.

Qin, Jian, Ying Liu, and Roger Grosvenor. 2016. “A Categorical Framework of Manufacturing for Industry 4.0 and Beyond.” *Procedia CIRP* 52: 173–78. https://doi.org/10.1016/j.procir.2016.08.005.

Rojko, Andreja. 2017. “Industry 4.0 Concept: Background and Overview.” *International Journal of Interactive Mobile Technologies (IJIM)* 11 (5): 77. https://doi.org/10.3991/ijim.v11i5.7072.

Rolls-Royce. 2017. “Our Stories - TotalCare®.” Accessed November 22. https://www.rolls-royce.com/media/our-stories/discover/2017/totalcare.aspx.

Rüßmann, Michael (BCG), Markus (BCG) Lorenz, Philipp (BCG) Gerbert, Manuela (BCG) Waldner, Jan (BCG) Justus, Pascal Engel, and Michael Harnisch. 2015. "Industry 4.0." *The Boston Consulting Group*, 20. https://doi.org/10.1007/s12599-014-0334-4.

Schlaepfer, Ralf C., Markus Koch, and Philipp Merkofer. 2015. "Industry 4.0. - Challenges and Solutions for the Digital Transformation and Use of Exponential Technologies."

Schumacher, Andreas, Selim Erol, and Wilfried Sihn. 2016. "A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises." *Procedia CIRP* 52: 161–66. https://doi.org/10.1016/j.procir.2016.07.040.

Schwab, Klaus. 2017. *The Fourth Industrial Revolution*. New York: Crown Business.

Shapeways. 2018. "Shapeways - Create Your Product. Build Your Business." Accessed October 13. https://www.shapeways.com/.

Stock, T., and G. Seliger. 2016a. "Opportunities of Sustainable Manufacturing in Industry 4.0." *Procedia CIRP* 40 (Icc): 536–41. https://doi.org/10.1016/j.procir.2016.01.129.

———. 2016b. "Opportunities of Sustainable Manufacturing in Industry 4.0." *Procedia CIRP* 40 (Icc): 536–41. https://doi.org/10.1016/j.procir.2016.01.129.

Strandhagen, Jo Wessel, Erlend Alfnes, Jan Ola Strandhagen, and Logan Reed Vallandingham. 2017. "The Fit of Industry 4.0 Applications in Manufacturing Logistics: A Multiple Case Study." *Advances in Manufacturing* 5 (4): 344–58. https://doi.org/10.1007/s40436-017-0200-y.

Strange, Roger, and Antonella Zucchella. 2017. "Industry 4.0, Global Value Chains and International Business." *Multinational Business Review* 25 (3): 174–84. https://doi.org/10.1108/MBR-05-2017-0028.

Szozda, Natalia. 2017. "Industry 4.0 and Its Impact on the Functioning of Supply Chains."

LogForumJ.LOG 134 (134): 401–14. https://doi.org/10.17270/J.LOG.2017.4.2.

Tesla. 2018. “Software Updates | Tesla.” Accessed December 6. https://www.tesla.com/support/software-updates.

Thames Water. 2017. Smart Water Networks. https://www.thameswater.co.uk/-/media/Site-Content/Corporate-Responsibility/CRS-201617/How-we-do-business/Case-studies/Smart-Water-Networks.pdf

Tjahjono, B., C. Esplugues, E. Ares, and G. Pelaez. 2017. “What Does Industry 4.0 Mean to Supply Chain?” *Procedia Manufacturing* 13: 1175–82. https://doi.org/10.1016/j.promfg.2017.09.191.

Vaidya, Saurabh, Prashant Ambad, and Santosh Bhosle. 2018. “Industry 4.0 - A Glimpse.” *Procedia Manufacturing* 20: 233–38. https://doi.org/10.1016/j.promfg.2018.02.034.

Wahlster, Wolfgang, Johannes Helbig, Ariane Hellinger, M A Veronika Stumpf, Joaquín Blasco, Helen Galloway, and Heilmeyerundsernau Gestaltung. 2013. “Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0.”

Wheeler, Andrew. 2015. “Lights-Out Manufacturing: Future Fantasy or Good Business?” Autodesk. Accessed November 19. https://www.autodesk.com/redshift/lights-out-manufacturing/.

Witkowski, Krzysztof. 2017. “Internet of Things, Big Data, Industry 4.0 - Innovative Solutions in Logistics and Supply Chains Management.” *Procedia Engineering* 182: 763–69. https://doi.org/10.1016/j.proeng.2017.03.197.

World Economic Forum. 2017. “Impact of the Fourth Industrial Revolution on Supply Chains.” *World Economic Forum*, no. October: 22. www.weforum.org.

Xu, Li Da, Eric L. Xu, and Ling Li. 2018. “Industry 4.0: State of the Art and Future Trends.” *International Journal of Production Research* 56 (8): 2941–62.

https://doi.org/10.1080/00207543.2018.1444806.

Zawadzki, Przemysław, and Krzysztof Zywicki. 2016. “Smart Product Design and Production Control for Effective Mass Customization in the Industry 4.0 Concept.” *Management and Production Engineering Review* 7 (3): 105–12. https://doi.org/10.1515/mper-2016-0030.

Zhou, Keliang. 2015. “Industry 4.0: Towards Future Industrial Opportunities and Challenges,” 2147–52.