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Industry 4.0 in focus: The Adidas Speedfactory

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Abstract: Industry 4.0 is the concept that is currently revolutionizing all production companies. It entails the connectivity and digitalization of the production process and could usher in an era of mass customization. The connectivity and digitalization of the production process and could usher in an era of mass customization. Adidas recognized the opportunity and decided to launch their first Speedfactories in 2015 with the aim of providing customizable shoes. They first opened a Speedfactory in Germany, and then in the United States. However, in 2019, Adidas decided to close these 2 factories in order to relocate them to Asia. In this thesis, we will investigate the reasons behind the failure of the Speedfactories.

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1. Introduction

It was in 2011, at the World Industry Forum in Hannover, Germany, when engineers decided on a new paradigm that will shake up future for production companies. This new paradigm is called Industry 4.0 or the 4th industrial revolution. This emergent industry stands for the convergence of the virtual world, digital design, management with real world products and objects. The aim of this Fourth Industrial Revolution is to seduce consumers with unique and personalized products and, despite low manufacturing volumes, to maintain profits. Nowadays, nearly a third (31%) of production processes and equipment already employ intelligent technology, which spawned from this revolution (impact, 2020).

This new paradigm is characterized by the digitalization of production lines, allowing for a total interoperability in the manufacturing processes. Under Industry 4.0, production will be information exchange and monitored machines, and manufacturing devices operating autonomously and smartly in interoperability. This leads to the advancement of industrial technologies that reduce labor, shorten product development time and use resources efficiently. One of the salient elements of Industry 4.0 is the smart factory, which boasts a new integration, in which not only all manufacturing assets (sensors, actuators, machines, robots, conveyors, etc.) are interconnected and exchange information automatically, but also the factory is conscious and smart enough to predict and take care of the machines, monitor the production flow and run the factory system. Furthermore, multiple processes in manufacturing, such as product design, production planning, production engineering, and production and services, will be simulated modularly and then tightly connected end-to-end, meaning that said processes are not only controlled by a decentralized system but also controlled interdependently.

Industry 4.0 is a response to the consumer interests that are constantly changing and becoming more and more complex as time goes by. In order to satisfy this increasingly volatile demand, mass production is no longer sufficient. It is therefore important to be able to provide a product that can be produced in large quantities and that is not standardized but instead customizable. Many of the technologies that Industry 4.0 has embraced have the potential to enable this era of mass customization. Among them, we count technologies such as Additive Manufacturing or 3D printing to be able to mass produce different products, the Internet of Things which allows real-time control each of the machines through sensors and actuators, cloud computing for the exchange of information in real time, Big Data for mass information gathering, Augmented Reality, which permits preemptive product visualization and customization, as well as many other technologies, on which this thesis will elaborate. Through these technologies and the possible synergies between them, Industry 4.0 features 6 key principles: Interoperability, Virtualization, Real-time capability, Decentralization, Service orientation and Modularity.

In 2015, Adidas introduced Industry 4.0 into its production facilities and committed to creating a smart factory in order to offer customizable athletic shoes. That same year, Adidas built its first Speedfactory in Ansbach, Germany. Establishing a factory outside Asia was unprecedented for Adidas, as they outsource 97% of their production there. The reasons that led Adidas to launch the Speedfactory were to increase speed of production and lead time, being closer to consumers and, meet the needs and expectations of consumers through their customization tool. The Speedfactory uses technologies such as 3D printing, robotic arms and computerized knitting, as well as other Industry 4.0 technologies, such as Augmented Reality or the Internet of things. The level of sophistication of these technologies allows for the production facility to swiftly react to changes in market requirements and to produce customized goods (Milasius, 2017). In 2017, Adidas opened a new Speedfactory in Atlanta in order to be closer and provide faster delivery to US consumers (Adidas, 2016). However, in 2019, Adidas closed their 2 Speedfactories to relocate them in Asia.

In this thesis, we will attempt to answer the following question: Does Industry 4.0 have the potential to be viable outside of Asia?

In order to do this, we will be focusing on the example of Adidas Speedfactories outside of Asia and assess their viability.

To answer the above research question a thorough analysis of the causes of the Speedfactories' failure and the reasons that drove Adidas to relocate them to Asia after this experience is required. The initial intent of Adidas was to do away with dependence on Asian expertise. Nevertheless, the eventual relocation of their factories to Asia in 2019 remains a testament to the failure of this attempt. We will thus elucidate the factors that led Adidas to discontinue their Speedfactories in Germany and America.

In order to properly understand the paradigm of Industry 4.0 and his impact, I have first read 2 books: *The Rare Metal War* by Guillaume Pitron and *The zero marginal cost society - The Internet of Things, the collaborative commons, and the eclipse of capitalism* by Jeremy Rifkin. It introduced me to the concept of Industry 4.0 and made me understand the importance of the advent of this paradigm. Throughout this thesis, 122 sources regarding Industry 4.0 and the Adidas Speedfactories have been consulted: 58 scientific and literature articles, and 64 online sources. In order to provide an accurate and complete list of Speedfactories' components in chapter **Erreur ! Source du renvoi introuvable.**, I have based this information on the Adidas video presentation and the analysis that has been done on it on the website Solereview. Extensive research on different companies that have collaborated with Adidas has also been conducted.

This thesis will first introduce Industry 4.0 through a literature review, in which its origin, definition, integration process, as well as the concept of smart factories will be presented. Subsequently, the 8 different technologies that make industry 4.0 possible will be presented and thereafter the 6 principles that industry 4.0 makes achievable. I will then

present the Mass Customization concept that is made possible by Industry 4.0 technologies. Additionally, 5 critical success factors for an efficient implementation of Industry 4.0 in an organization will be put forth. In order to best define said success factors, I have collected 7 articles that list the CSFs and have highlighted the elements that were most frequent, redundant and relevant (See Appendix 1).

Then, the specific case of Adidas Speedfactories, including the reasons for their lack of viability will be addressed.

Finally, Chapter 4 will focus on case analysis. The Adidas case will be reexamined in light of what we have taken away from the literature review in order to understand the reason why the success of Speedfactories has been limited. This will be completed by means of a comparison of Speedfactories against the 6 principles of Industry 4.0., and the Mass customization concept. More precisely, we will examine which critical success factors have played a role in determining the viability of Adidas's endeavours and, eventually, informed their decision to relocate their production activities to Asia.

2. Literature review

2.1. Historic background

As the name Industry 4.0, or the fourth industrial revolution, suggests, it took three previous revolutions to make this one happen. Each industrial revolution has introduced a series of innovations that have fundamentally changed the way we work. New jobs, new industries, new professions have emerged in each of them. The explanation for a transition from one industry to another is the evolution of science that enables a shift in energy or labor efficiency (Gunal, 2019).

The first industrial revolution started around 1750 with the steam machine innovation. This first revolution was possible due to the increased application of science to the industry. The change in the way production was carried out shifted from agriculture and crafts to manufacturing with machines. Craftsmanship has been replaced by mechanical production, factories will replace factories and craft workshops. In the factories, the revolution corresponds to the use of the steam machine as an engine to drive the machines allowing increased rates of production (Gunal, 2019).

The second industrial revolution began in the 1900's. The production machines were running on electricity and oil. This made possible the mass production of identical products, the process of making steel and the manufacture of machine tools on a large scale. The speed of production then increased, but offered very low design and manufacturing flexibility (Haleem & Javaid, 2019).

During the two world wars, two major innovations appeared: digital computers and the Internet. These technologies have led to the emergence of the third industrial revolution that came around 1960. This period is characterized by the emergence of electronics, information and communication technology (ICT) to automate production. This was also the beginning of robotics and flexible production tools. ICTs have allowed a considerable improvement in production systems. Workers no longer had to spend time in front of the machines. They did, however, have to turn it on and observe how things were going (Xu & al., 2018).

Nowadays, production systems still operate in this way. However, we are at the beginning of the 4th industrial revolution more commonly known as Industry 4.0. The basic idea is to transfer the control of manufacturing to the "intelligence of the machines". We will be moved into the era of mass product customization made possible by the new interconnected technologies (Gunal, 2019).

2.2. Industry 4.0

The first idea and use of the term “industry 4.0” was introduced during the Hannover Fair in Germany in 2011. The term was invented by Klaus Schwab, founder and executive chairman of the World Economic Forum (Xu & al., 2018).

The main characteristics of industry 4.0 is digitalization and automation. The connectivity between all the devices which will allow to perform better in all aspects of the production by increasing the speed of the machines, their performance, reducing the raw materials used. Driven by the emergence of new technologies and the increasing development of information and communications technologies (ICT), Industry 4.0 refers to a new generation of connected, robotic and intelligent factories that significantly improves the supply chain as we know it by taking it to the next level. With the digital revolution, the boundaries between the physical and digital worlds are blurring. Giving life to an interconnected 4.0 factory in which people, machines and products interact. The objectives of Industry 4.0 will be to reach the next level in terms of operational efficiency, productivity and machine automation, and will allow no longer mass production but mass customization (with 3D printers for example). The 6 principles of Industry 4.0 are interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity (Shafiq & al., 2015; Hermann & al., 2015; Lu, 2017; Feet in 4.0, 2018):

Table 1. The six principles of Industry 4.0

Principle	Description
Interoperability:	Cyber-physical systems make it possible for people and Smart Factories to communicate and connect with each other.
Virtualization:	By connecting sensor data from cyber-physical systems to virtual shop floor models and simulation models, a virtual copy of the smart factory is created.
Real-time capability:	Data is gathered, analyzed and immediately converted into insights.
Decentralization:	Cyber-physical systems are capable of making autonomous choices and producing locally.
Service orientation:	All cyber-physical systems and human services are provided internally or even outside the company.
Modularity:	Smart factories are highly flexible and can accommodate changing needs by replacing or extending individual modules.

Note: Adapted from “Industry 4.0: A survey on technologies, applications and open research issues” by Lu, Y., 2017, *Journal of Industrial Information Integration*. And from “Design Principles for Industrie 4.0 Scenarios: A Literature Review” Hermann, M., Pentek, T., & Otto, B., 2015, *Technische Universität Dortmund*.

The goals of Industry 4.0 are to achieve Smart Factories, which we will discuss later (Gunal, 2019). In Industry 4.0, the manufacturing process will involve more sensors, actors, microchips and autonomous systems due to the accelerated development of technologies (lu, 2017).

If the disruptive and triggering element of the 1st industrial revolution is steam power, the one of the 2nd industrial revolution is electricity and the assembly line, and the one of the 3rd industrial revolution is electronics and IT combined, it could be that the disruptive factor of the 4th industrial revolution is artificial intelligence (AI) (Echeberria, 2020).

2.2.1. Three kinds of integration

The integration of industry 4.0 can be outlined in three dimensions: horizontal integration, vertical integration and end-to-end engineering integration.

Horizontal integration in a macro perspective describes the inter-firm and intra-firm networks in order to enable collaboration between firms or organizations in the value chain. More than one organization cooperates to provide high-quality products and services for business success. It will therefore create a new digital ecosystem through digitization and networking throughout the value chain of a product's life cycle and between surrounding product life cycle value chains (Sony, 2018; Stock & Seliger, 2016). Concerning the micro perspective, the horizontal integration consists of good management of Industry 4.0 technology tools to ensure that machines, IoT devices and engineering processes cooperate harmoniously to provide accurate production progress data. This data is used to improve the production process.

Vertical integration is the set of hierarchical sub-systems integrated within the organization to create a flexible and reconfigurable manufacturing system within the organization. The different sub-systems including activities associated with the value chain such as marketing and sales or technology development will be inter-connected to the ERP system. Smart machines within the organization will adapt autonomously to the different products. This will be made possible through proper management of the big data.

End-to-End Engineering refers to the intelligent cross-linking and digitalization at each phase of a product's life. From the acquisition of raw materials, to the production system, to the sale of the product and to the end of the product's life. In other words, End-to-end integration meets the needs of each customer and enables the creation of customized products and services throughout the value chain. Customer needs analysis, product design and development, production, services, maintenance and recycling are examples of product-centered value creation processes that could be automated and self-organized

according to customer needs using powerful software tools. For example, the combination of 3d printers linked to a smart machine and intelligent software (which can receive information from a point of sale and treat it directly in the manufacturing place) can allow the creation of customized products and services (Copadata, 2018).

2.2.2. Smart factory

Smart factory is the vision of industry 4.0. In other words, it is about setting up systems in factories in which machines are connected to each others, but also and above all to the Internet in order to ensure optimal control of production processes. Smart factories represent the link between digital and physical production networks. The fourth industrial revolution goals are to achieve the smart factory and thus, removing human from the "supervision" of the machines (Gabriel & Pessl, 2016).

In a work environment applying the principles of Smart Manufacturing, the aim is to automate as many operations as possible so that they are carried out with maximum efficiency. The main objective here is to gain efficiency, by reducing both costs and time of production. To achieve this, the central element of this type of organization is data. It is first collected directly from the equipment (especially collected by the Internet of Things technology sensors). Then they are analyzed by artificial intelligence and machine learning to enable the right decisions to be made in the service of manufacturing performance (Lu, 2017).

Smart factory enables enterprise interoperability or machine learning. This is the ability of two systems to mutually understand each other and use each other's functionality. These two systems can exchange data and share information and knowledge. Industry 4.0 interoperability will summarize software components, application solutions, business processes and business context throughout the diverse, heterogeneous and autonomous process. In smart factories, there are stand-alone machines that can perform regular operations and decide what to do in special situations. They can indicate when to replenish inventory and how much inventory to maintain, and easily switch between tasks. (Gunal, 2019).

2.3. Technologies in Industry 4.0

Industry 4.0 encompasses many technologies (lu, 2017). Assembling all the 4.0 technologies was not easy knowing that many authors and companies have talked about them. In order to provide a relevant list. We chose 8 technologies we found in the industry 4.0 literature that are for us the most representative. It is important to notice that these technologies already existed before industry 4.0.

2.3.1. Internet of Things (IoT)

The definition of the Internet of Things is not fixed, as it has been constantly evolving since the 1980s. In the context of industry 4.0, IoT refers to devices and machines interconnected and equipped with electronic sensor, actuators or other digital system that allow the data collection and exchange (Li Da Xu, Eric L. Xu & Ling Li, 2018). This enables to equip physical objects with a virtual system that collect and send information to a network and therefore, have a real-time visibility and traceability of production processes (Zhong & al, 2017). The IoT Transform typical production resources into smart manufacturing object, and thus facilitates the partnership between Human to machine and even machine to machine to boost the performance of a factory. The Internet of Things uses different kind of information technology (IT) for data collection and sharing, such as QR code or Near Field Communication (NFC). But the two cutting edge technologies it used is the Radio Frequency Identification (RFID) readers and tags, and Wireless Sensor Networks (WSN) (Ardito & al., 2017; Zhong & al., 2017; Da Xu & al., 2018).

RFID is a method for remotely storing and retrieving data using markers called radio tags. Radio tags are small objects, such as self-adhesive stickers, that can be stuck or embedded in objects or products. Radio tags consist of an antenna associated with an electronic chip that enables them to receive and respond to radio requests from the transceiver. It is frequently used in supply chain management to see the actual stock movements of items in a warehouse for instance. RFID is one of the pillars of IoT. It is used in many different industries, such as transportation, healthcare, materials management, retailing, etc. Zara, Wal-Mart, Decathlon and Macy's Inc use RFID in their workshops, assembly lines and warehouses to facilitate and improve their Supply Chain Management (Da Xu & al., 2018).

Internet of Things can be compared to an ubiquitous computer. It allows companies' businesses to be more optimized or developed by having at their disposal information that was previously unavailable. By facilitating and further developing supply chain management, it enables companies to streamline their processes in order to improve profitability. According to McKinsey, the economic impact of IoT in factories by 2025 will reach \$3.7 trillion per year.

2.3.2. Cyber-Physical System (CPS)

The cyber-physical system consists of microcontrollers that control sensors and actuators. These elements are equipped with communication capacity to exchange data and training between embedded computer terminals which enable a high degree of coordination and combination between physical objects and their computational elements or services. Cyber-physical system is autonomous and closely connected to the surrounding physical world and their ongoing processes (Hohmann, 2017; lu, 2017). It is

called a cyber-physical system because the system is able to interact with the physical world, and to interpret data intelligently and in real time (Zhong & al, 2017).

CPS enables the transformation of existing factories into smart ones by improving both productivity and resource efficiency, therefore allowing more flexible models of work organization, having a real-time advantage and reducing costs while improving product quality through data collection and analysis (GTAI 2014; lu, 2017). CPS will also empower Industry 4.0 to remove the boundaries between the virtual and physical worlds by merging them. Industry 4.0 and its production systems through CPS will be collaborative, involving physical agents, software agents and human agents. Its integration in the industry and in the value chain will therefore greatly facilitate production and manufacturing (Da Xu & al., 2018; Zhong & al, 2017).

2.3.3. Cloud computing

The cloud is a model in which anyone can "consume" or request services that are hosted on an online platform. The technical infrastructure does not need to be owned as the data are located at the cloud provider's site and belong to this latter. With the current progress of ICT, cloud computing can be considered as the "fifth utility", joining water, electricity, gas and telephone (Buyya & al., 2009).

Cloud computing has 5 main characteristics: Service on demand, measurable service, mutuality of resources, elasticity, and broad network access. We can therefore talk about « service on demand » because a customer can make a request for a resource and the response from the cloud is immediate. Then, service from the cloud is measurable, the customer and the provider must be able to measure the use that is made of the resources, a customer only pays for what he consumes. The cloud also offers the mutuality of resources, the hosting provider has a huge amount of IT and these resources are shared between all customers according to demand, which allows elasticity by dynamically allocating resources upwards, downwards, permanently, temporarily and in a very quick way. And finally, broad network access, these processing centers are generally connected directly to the Internet backbone to benefit from excellent connectivity. Major suppliers are spreading the processing centers around the world to provide access to systems in less than 50ms from any location (Figer, 2012; Zhong & al., 2017)

The cloud is hence built on 3 levels of services. The first level is the Infrastructure as a Service (IaaS) which allows a user to rent computing and storage resources, network capacity and other resources such as firewalls or load sharing. The user does not manage or control the underlying Cloud infrastructure but has control over operating systems, storage and applications. A prime example of this type of service is Amazon Web Services, which provides computing, storage, and online databases. The second level is Platform as a Service (PaaS). Cloud allows the use of a shared application that runs on a cloud

infrastructure. The user, does not control the functions of the application except for a few limited user functions. The third level is Software as a Service (SaaS). The user accesses the application shared by the network through various types of terminals such as the web browser. It is on these applications that the end user will be able to make his service request (Figer, 2012).

2.3.4. Big Data

Big data has been described as the growing and proliferating influx of data from multiple sources, mainly interconnected through the Internet. Large-scale data collection began in 2012 with the advent of new technologies such as connected objects (notably due to IoT development) that significantly increase the volume of data to be processed. However, at that time, we did not have the technology we have now to analyze and exploit them (Ardito, 2017). According to Strategy Analytics, there were 22 billion connected objects in the world in 2019 and they predict 38.6 billion connected objects by 2025. More and more data will therefore be generated and this exponentially (Mac4ever, 2019).

Big Data refers to all the digital data produced by the use of new technologies. Big data has 3 main characteristics that complicate its analysis and exploitation: volume, velocity and variety of data. There are incommensurable volumes of data being generated permanently which are seen as a rich and continually renewed source of information. However, this data is often overabundant and heterogeneous which does not always make it relevant. Big Data analysis therefore consists in drilling this huge database to retrieve the useful data using powerful algorithms (Le Doussal, 2021; Y. Zhong & al., 2017).

Big Data can significantly benefit companies by adding value and making it easier to meet customer expectations. Intelligent sensors (IoT) placed on connected objects continuously provide masses of information on the behavior of machines and their users. In addition to facilitating the targeting of customers, there are many examples of the benefits of Big Data for a manufacturing company. It will now be possible to perform predictive maintenance by anticipating equipment failure by analyzing the data generated by this equipment through sensors, and thus schedule maintenance operations at the best time. The optimization of processes or equipment will be facilitated by finding the parameters that influence performance (material consumption, energy consumption, productivity...) and defining the optimal conditions to be applied. Finally, by using forecasting algorithms, we will be able to anticipate the behavior of the production line according to parameters that may be sudden (quality of raw materials, weather conditions...) and to modify the piloting parameters to always be in the optimal conditions. All these examples will allow to considerably reduce costs while increasing reliability (Cura, 2019).

2.3.5. Additive Manufacturing (3D printing)

Additive Manufacturing (AM), or 3D printing designates the set of methods for manufacturing a physical object by superposition of layers of materials from a 3D digital model. it will contribute to solve one of the primary challenges of the industry 4.0, i.e., mass customization. Many materials are suitable for 3d printers. Metal, which is one of the major resources in manufacturing and engineering industries, can be manufactured by AM technique. Additive manufacturing also enables to use liquid and solid materials simultaneously in the process, to print an electrical circuit. AM is becoming more and more developed and even allows to print textile and therefore starts to be used increasingly in the clothing industry (see Figure 1). This will bring many opportunities in terms of material as seen above, size as a 3D printer can print nanoscale objects to large parts and functionality enabling the production of goods on demand (Dilberoglu & al., 2017).

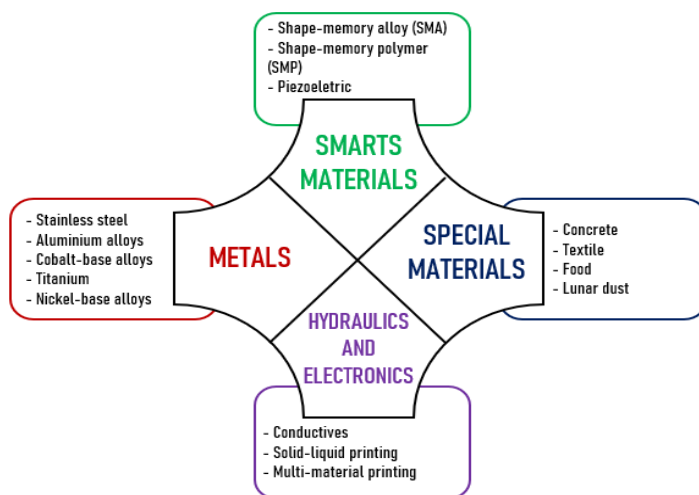


Figure 1: the different applications of additive management (Dilberoglu, U., Gharehpapagh, B., Yaman, U., & Dolen, M. (2017). *The role of additive manufacturing in the era of Industry 4.0*. pp. 547. doi:10.1016/j.promfg.2017.07.148).

Additive Manufacturing will bring considerable help and benefits to the supply chain of a manufacturing industry, allowing consequently to develop mass customization in an easier way. Furthermore, Prototyping will be made far less constraining and expensive. Another advantage of AM is that it reduces waste by using only the materials it needs, the rest can be reused. In other words, 3D printing enables faster, more accurate and more flexible production. (Haleem & Javaid, 2019).

2.3.6. Augmented reality

Augmented Reality (AR) enables digital image information to be sent to a user via goggles or tablet and combined it with real world elements. In concrete terms, this means that a non-skilled user can be guided through the assembly process by a skilled operator in a control room located elsewhere (Fraga-Lamas & al., 2017). A common example of how the AR works in maintenance is as follows: An operator 1 on the site, equipped with a tablet or glasses, sends a picture or retransmits the situation live to a competent operator who will examine and send back the picture with information or add live information to the interface of operator 1 in the form of symbols, text or sketches so that he can solve the problem easily (see Figure 2) (Masoni & al., 2017). Currently, there are 3 visualization techniques that augment the environment via AR. Firstly, techniques that augment the environment by adding virtual objects (realistic). Secondly, Meta-graphic, which allows to add information in a way that distinguishes it from the environment, such as arrows, sketches or annotations. And thirdly, techniques that modify by changing the contrast or saturation of colors to guide the user (Paelke, 2014).

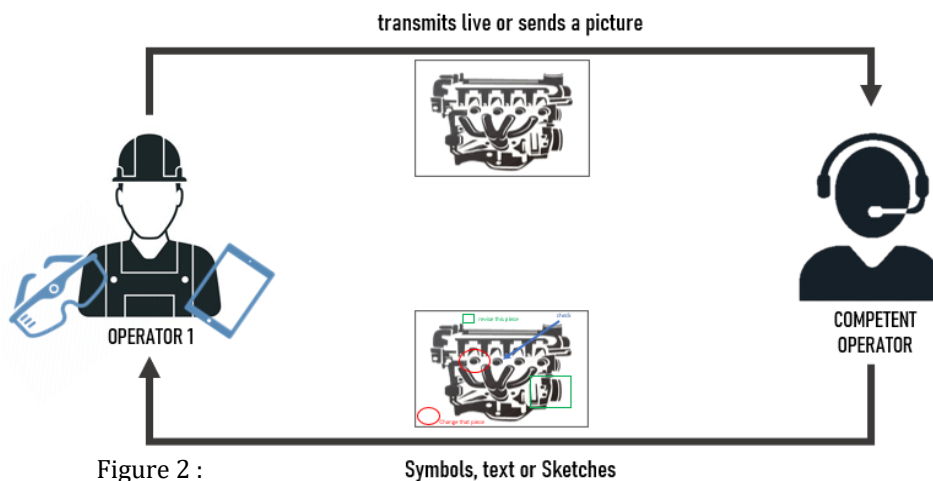


Figure 2: Example of the functioning of Augmented Reality (Paelke, 2014).

AR can be very useful in maintenance by reducing time and errors in tasks but can also be useful in many other fields, such as service (manuals and instructions, service inspections, remote expert guidance,...), manufacturing (Quality assurance, maintenance and assembly work instructions, performance dashboards...), sales and marketing (logistic and retail space optimization, augmented brand experience, augmented advertisement,...), design (inspection of digital prototypes, augmented interface, error diagnosis,...), operations (heads-up displays, digital product controls, augmented operator manuals,...) and training (job-specific training, safety training, expert coaching,...) (Koster & al., 2006).

2.3.7. Blockchain

As previously defined with the different technologies, the principle of Industry 4.0 is hyper-connectivity. This hyper-connectivity leads to system vulnerabilities increasing the risk of cyber-attacks. In order to counter technological threats, blockchain helps by providing a network of blocks rather than containing the protection in a single epicenter. This network is often compared to an account book in which all data or transactions exchanged/transferred within a company and with its external environment are recorded. When an action is performed, the data are validated and form an associated block of a computer identifier. The block is then added in the blockchain with an asset that makes them unfalsifiable. Each of the blocks are linked to each other by their identifiers; it is therefore impossible to modify one of them without modifying all the others. It offers a quasi-complete security as this database is accessible to all the users of this blockchain, which makes it immutable. It is said to be unforgeable because all the information contained in the database is unerasable and traceable. Each user can therefore be informed of a possible modification in case of intrusion in the chain (Zhong & al, 2017).

Blockchain technology is usually associated with cryptography such as the well-known Bitcoin. However, it is also used in many other applications, including securing Industry 4.0. The transparency of this system makes it possible to follow the entire life cycle of a product, from raw material to finished product. This provides traceability to optimize logistics (delivery times, tracking suppliers who have supplied non-compliant products, etc.) (Eich Gozzi, 2018).

It also enables the use of "smart contracts". A type of contract in digital format, they take the form of codes inserted in a blockchain allowing assets to be exchanged from one entity to another automatically (according to predefined management rules). These intelligent contracts allow the automation of the production chain as a complement to a traditional ERP (e.g. automatic secure ordering of raw materials when stock levels are low) (Fu & al, 2018).

2.3.8. Artificial intelligence (AI) and the synergy among the Industry 4.0 technologies

In 2004, Dimiter Dobrev, a renowned Mathematician and Computer Scientist, has defined artificial intelligence as (Dobrev, 2004):

“AI will be such a program which in an arbitrary world will cope not worse than a human.”

In other words, artificial intelligence (AI) is the capacity of a digital machine or computer-controlled robot to undertake tasks typically associated with intelligent beings. It is frequently used to refer to the development of systems with the intellectual processes

characteristic of humans, such as the capability to reason, to discover meaning, to generalize or to learn from past experience (Copeland, 2020). Artificial intelligence may be the most applicable disruptive technology in the near future. This is supported by The One Hundred Year Study on Artificial Intelligence, launched in the autumn of 2014 and published by Stanford University. AI was developed as a science and a set of computer technologies modelled on the way people use their nervous systems and bodies to feel, learn, reason and act, but which generally work in very different ways (Echeberria, 2020; Nilson, 2010). What really makes the transition between the 3rd and the 4th industrial revolution is the fact that artificial intelligence will be able to link all these technologies by making them understand each other. It can be considered as the cement of this new revolution (Echeberria, 2020).

The industry 4.0 technologies are not sealed and create synergies between technologies like AI, Blockchain, Big Data and IoT. Everything will be connected to the cloud in the future (Segura, 2018). Although the above-mentioned technologies already exist, more will be needed to achieve the goals of Industry 4.0. For instance, robots in the manufacturing sector are prevalent, but in the future, robots will no longer need human involvement in decision making. This is rather challenging today, but advances in artificial intelligence (AI) and sensor technology offer the possibility of achieving this (Gunal, 2019). Many synergies are essential and complementary in Industry 4.0. For example, the IoT needs the cloud to work effectively, as computing is necessary for the cloud to work. AI was only a model until the emergence of big data. The convergence of technologies is simply unavoidable and usually beneficial, particularly now, at the dawn of the 4th industrial revolution and the future machine economy (or machine learning). The data (as known as Big Data) collected by IoT devices (RFID, Sensors...) is increasingly important and needs to be processed efficiently. This data is a core component of applications to develop AI and machine learning, which are becoming applied to a broad range of uses. Big data analysis is the practice of examining huge datasets that contain a range of data types - i.e., big data - to discover hidden models, unknown correlations, market trends, customer preferences and other information. Recently, blockchain has also emerged as a boundary for IoT and other data technologies respectively. The ability of blockchain technology to ensure data accuracy makes it valuable for a number of AI applications, both in terms of supplying data to AI systems and in terms of recording the results of AI systems. Furthermore, there is no doubt that AI and blockchain are two key technologies. The machine economy, also known as machine-to-machine or machine learning, is going to be the key element of Industry 4.0 and is made possible by AI. We are now talking about integration of AI, IoT, blockchain and cloud computing. Traditional and current data analysis, computing, security and connectivity solutions are not sufficiently powerful or smart enough to control a vehicle, robot or highly autonomous machine. Therefore, through the convergence of these 4 technologies, machines can navigate quickly, dynamically and securely with little or no human intervention (Rabah, 2018). AI is permeating virtually all technologies and, if defined and properly framed, can enable more

dynamic, flexible and potentially autonomous systems. Research into collaborative systems is looking at models and algorithms for developing autonomous systems capable of working in collaboration both with other systems and with humans (Echeberria, 2020).

Such tendencies direct the current "hot" areas of AI research towards fundamental methods and application areas. The first "hot" topic concerns machine learning at large scale that is about the development of learning algorithms, as well as the upscaling of established algorithms, in order to work with massive data sets. Reinforcement learning is a setting that moves the goal of machine learning from pattern detection to experience-based sequential problem solving. It allows AI applications to evolve into real-world actions. Although it has been largely confined to academia in recent decades, it is now experiencing some practical success in the real world. Robotics research is currently devoted on how to train a robot to interact with the surrounding environment in a predictable and generalizable way, how to assist in the operation of objects in interacting worlds and how to interact with humans. IoT research focuses on the idea that a large range of devices, including appliances, vehicles, buildings and cameras, can be networked to gather and share their wealth of sensorial data for intelligent use. Concerning the IoT, digital twins, which is a digital representation of a real-world entity or system, are complementary to it, providing information about the state of each connected real-world object, responding to changes and improving operations. Digital twins will be available for billions of items, with an estimated 21 billion connected sensors and endpoints by 2020. Smart objects employ AI and machine learning to interoperate more intelligently with humans and their environment. Some smart devices would not exist without AI, but others are existing objects (e.g. a car) that AI enables to be smart (e.g. a smart car). It is to be expected that autonomous smart objects will give way to a cluster of collaborative smart objects. In such a pattern, numerous devices will operate together, whether independently or with the help of a human. The military is at the forefront of this field and is exploring the use of swarms of drones to attack or defend military bases (Echeberria, 2020).

2.4. Contributions to industry

As mentioned in section 2.2, Industry 4.0 offers 6 principles to the manufacturing industry:

Table 2. The six principles of Industry 4.0

Principle	Description
Interoperability:	Cyber-physical systems make it possible for people and Smart Factories to communicate and connect with each other.
Virtualization:	By connecting sensor data from cyber-physical systems to virtual shop floor models and simulation models, a virtual copy of the smart factory is created.
Real-time capability:	Data is gathered, analyzed and immediately converted into insights.
Decentralization:	Cyber-physical systems are capable of making autonomous choices and producing locally.
Service orientation:	All cyber-physical systems and human services are provided internally or even outside the company.
Modularity:	Smart factories are highly flexible and can accommodate changing needs by replacing or extending individual modules.

Note: Adapted from “Industry 4.0: A survey on technologies, applications and open research issues” by Lu, Y., 2017, *Journal of Industrial Information Integration*. And from “Design Principles for Industrie 4.0 Scenarios: A Literature Review” Hermann, M., Pentek, T., & Otto, B., 2015, *Technische Universität Dortmund*.

2.4.1. Interoperability

Industry 4.0 and smart manufacturing require the integration of various distributed cloud-based services, companies, smart factories, smart devices and workflows. In order to integrate these systems, there must be a seamless interchange of information between these disparate systems that operate according to a wide variety of communication standards. This has introduced an unparalleled opportunity challenge known as interoperability (EnviroTREC, 2020).

Regarding the definition of interoperability, it can be defined as the capability of two or more entities to interoperate and cooperate (Zeid & al., 2019). The ISO 16100 standard defines interoperability as "the ability to share and exchange information using common syntax and semantics to satisfy an application-specific functional relationship through a common interface" (ISO, 2018).

The central idea of interoperability in industry is integration, which is also the focus of IoT and cyber-physical systems (CPS). Industry 4.0 has three types of integration,

horizontal integration, end-to-end integration and vertical integration, as discussed in section 2.2.1. (EnviroTREC, 2020). Industry 4.0 requires production lines to be dynamically optimized. Devices play a central role in these production lines, which are becoming increasingly complicated and highly difficult to supervise and monitor by humans. This tendency favors the development of devices capable of dynamically detecting and adapting to each other to optimize production flows. Internet of Things (IoT) research is attempting to enable such devices with sensors and captors, and, as a result, can permit (i) collecting, (ii) storing, (iii) elaborating and (iv) acting on information produced and shared across all value chains autonomously (Lelli, 2019). As long as IoT and industrial automation standards mature, companies can expect to continue to face challenges in introducing IoT devices and other Industry 4.0 technologies into their organizations. These challenges will involve both the initial integration task and the provision of service assurance for current operations (Curran-Hays, 2017).

Designers of manufacturing processes and operations personnel will need to give special attention to these challenges when working with Industry 4.0 technologies in their work environment (Curran-Hays, 2017). For example, production equipment must regularly update each other while simultaneously informing the monitoring systems of process changes and possible errors or failures. They must also be able to interact with cloud-based systems to obtain the services required. The software underpinning these components and services generally must be able to interact by developing an understanding of the shared language or syntax that each uses to interact with the outside environment. New paradigms are being created as the synergy effect between technologies and new needs emerge (Zeid & al., 2019).

Interoperability in an industry enables systems, units or forces to perform tasks for other systems, units or forces, to receive services from others and to use the traded services to enable them to work together efficiently. It also enables the use of IT tools that help coordinate work and information flow across organizational borders, primarily concentrating on inter-enterprise distributed flows. Most importantly, it provides the ability to embed information, functionality and processes in a semantic manner (Zeid & al., 2019).

2.4.2. Virtualization

Virtualization is the second Industry 4.0 principle. It is possible to virtually reproduce situations as they occur on the shop floor through virtual reality technologies within current immersive and interactive decision-making systems. In product manufacturing, Virtual Reality (VR) or Augmented Reality (AR) has a major role to play in all product lifecycles, from conception to manufacture. It allows manufactures to experiment with scenarios and designs before products are manufactured, improving productivity and reducing the cost of production. AR also enables manufacturers to include customers in

the design and engineering of the products (Adhikari, 2018). Virtualization can also digitally create a 'copy' of the warehouse by combining sensor data collected from physical process and equipment monitoring with virtual warehouse models and simulation patterns. This allows monitoring of increasing complexity, decreasing device downtime and improving performance through a 3D interface (Swisslog, 2017).

In Industry 4.0, virtualization encompasses several technologies such as Cloud Computing, Augmented Reality and the Internet of Things (IoT). Virtual applications become an essential part of this process. To ensure that the implementation of virtualization succeeds, a more coherent and communicative IoT deployment must be guaranteed to collect and process data from any platform and any location (Bonuccelli, 2017).

The adoption of VR softwares and hardwares in the manufacturing sector presents several challenges, as it is evolving rapidly. As a result, the industry needs to be flexible to change. There exist challenges regarding the communication, computing, storage and energy demand technologies used in VR. A factory that wants to implement virtualization must first implement Industry 4.0, then the 3D factory using VR technology, which will serve as a lever (Adhikari, 2018).

2.4.3. Real-time capability

Real-time capability enables immediate and timely decisions through real-time data collection and analysis (RMIT University, 2018). Industry 4.0 seeks real-time data for a real-time supply chain in a real-time economy (I-Scoop, 2021).

With technology such as IoT, problems can be solved before they even occur. Warnings can be put in place, assets can be maintained proactively, real-time monitoring and diagnostics become possible, and engineers can solve problems, if they occur remotely (I-Scoop, 2021). This makes it possible to see what is really going on in the company such as examining processes that need to be improved, finding out where the productivity opportunities are and analyzing micro-trends (RMIT University, 2018).

This requires the entire production system in its environment to be connected to intelligent sensors, software, IoT technologies, knowledge systems AND the customer. Automation has a major role to play, as do typical components of cyber-physical systems and the Internet of Things, which allow quality aspects to be monitored in real time and errors to be reduced by machines (I-Scoop, 2021). Most companies already have access to vast amounts of real-time data thanks to the proliferation of sensors and Internet-connected devices. The challenge lays in processing and analyzing this data in order to continuously optimize business operations. With tools such as open source and cloud computing, this information can be processed in real time with no need to wait for reports,

with numerous services providing integrated analytics that can be accessed anywhere at any time (RMIT University, 2018). Speed not only represents a strategic advantage and a customer requirement in an escalating real-time economy, it also represents alignment, affordability and value creation. (I-Scoop, 2021).

2.4.4. Decentralization

Industry 4.0 aims to facilitate decentralization, with systems being moved to components rather than a mainframe to allow for unlimited expandability and adaptability. Cloud-based data storage and transfer is a form of decentralization, as well as the process of automating manual and repeatable tasks. Both reallocate duties or tasks remote from a central location. All Industry 4.0 technologies tend to be decentralized. For example, in the area of advanced manufacturing, additive manufacturing allows companies to operate small decentralized factories in different locations (RMIT University, 2018). IoT will lead to smart factories and environments where computers can monitor the physical processes of the factory and take decentralized and independent actions (Bonuccelli, 2017). Conventional IoT relies on centralized infrastructures which are vulnerable to a number of types of cyber-attacks. Blockchain technology is moving these infrastructures to a decentralized form (Umran & al., 2021). Blockchain technology offers decentralization, transparency and immutability, possibly providing a strong fundamental system behind Industry 4.0 (Fu & al., 2018).

Through the adoption of a decentralized infrastructure, the problems of single point of failure, latency and bottlenecks are resolved, and the necessity of a third-party relationship, which usually increases the execution time required for authentication, is eliminated (Umran et al., 2021).

The information systems infrastructure is typically based on legacy software such as enterprise resource planning (ERP) or other centralized software. The primary challenge lies in synchronizing the information stocked in the ERP and the information maintained in the manufacturing system, and the secondary challenge lies in achieving real-time updating of information about unexpected events (Marques & al. 2017).

2.4.5. Service-orientation

Service-oriented means considering the functions of production processes as a set of services. These services must be available on the IoS (Internet of Service) through other systems. These services could be delivered both internally within the same manufacturing unit and beyond the boundaries of the manufacturing unit. Therefore, it is a matter of considering aspects of manufacturing functions and elements as services (Al-Jaroodi & al., 2018). Companies adjust to changing customer demands and expectations as they occur, providing a customized service. Consequently, the focus in all industries is shifting from

products to customers and from mass production to customized services (RMIT University, 2018). Service orientation assumes that Industry 4.0 will lead to new business models where services can be operated via the Internet of Services. Being able to design products that can be remotely controlled and supervised through the internet of services in real time (Pelizzo, 2016). For example, in the area of advanced manufacturing, technologies such as additive manufacturing allow factories to rapidly and cost-effectively produce small batch and customizable products (RMIT University, 2018).

Industry 4.0 is about connecting several manufacturing devices, manufacturing robotics, other manufacturing-related equipment and cloud-based manufacturing in a virtual environment. This virtual environment offers services using connected components which can be integrated to create and exploit Manufacturing 4.0 applications. There are many forms of services via cloud manufacturing: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), Software as a Service (SaaS), manufacturing data analytic as a service, manufacturing simulation as a service, etc (Al-Jaroodi & al., 2018).

In order to differentiate themselves, companies need to focus on a unique model through a service-oriented model. To do this, the company needs to focus on its core functions by starting to identify repetitive and non-core activities that can be eliminated or reduced (RMIT University, 2018).

2.4.6. Modularity

Modularity referred to the capacity of companies to respond flexibly to shifting industry requirements and demands. In general, modularity is envisaged either by dividing the company into small, well-defined teams that focus on specific elements of the company's operation, or by implementing modular systems such as software platforms where services can be purchased as needed. This differs from outsourcing as modular systems are developed to interact with and connect to the larger business. This allows companies to focus on what they do best. The value offered to the customer is thus increased in many ways through staff becoming specialists in core activities. In order to respond more quickly to changing market conditions, core activities can be extended as the business grows (RMIT University, 2018).

To integrate modularity into one's business, it is necessary to clearly differentiate identifiable blocks, which can be easily loaded on another manufacturing process line to fulfill the purposes of manufacturing different products, variations of products, or increasing production volume. It is therefore necessary for supply chains to be responsive and agile (Gupta, 2018).

By modularizing such a product design, the product can be pushed out, the manufacturing cost reduced, the assembly time shortened and the product families strengthened, thus supporting lean and flexible manufacturing processes (Gupta, 2018).

2.5. Mass Customization (MC)

One of the major changes that Industry 4.0 will enable is the transition from mass production (supply chains are based on the "push" model) to mass customization (supply chains are based on the "pull" model) (Luenendonk, 2019). The smart factories of the future will be independent units, capable of planning, organizing and even controlling production themselves. This is why Industry 4.0 is the key to the realization of Mass Customization which is focused on the individual needs of customers by manufacturing companies (Zawadzki & Żywicki, 2016). This is made possible by the various technologies and solutions proposed by Industry 4.0 as described above (Downey, 2021). Mass customization is the process of making manufacturing processes sufficiently flexible to produce products based on the customer's specific requirements, while keeping costs low. It maximizes both customization and mass production, leading to a cost-effective manufacturing system (Zhang, 2020). This contradicts somewhat with the principles of classical production as MC combines the advantages of single item production (individually and accurately) and mass production (rapidly and cheaply) (Zawadzki & Żywicki, 2016).

Nike By You or NikeiD is a good example of mass customization in both manufacturing and marketing. It offers customers the opportunity to customize their own Nike products, including clothing and footwear, from colours and materials to styling (WallStreetMojo & Vaidya, 2020).

2.5.1. Advantages and type of Mass Customization

Through mass customization, customers are able to personalize products by choosing specific colors, sizes, features, versions, etc. By optimizing customer satisfaction in this way, the risk of returns is reduced. MC also allows production to be based on demand so that companies do not risk their capital in potential stocks. Mass customization is an optimized solution to achieve both volume and flexibility (Zhang, 2020).

There are 4 types of Mass Customization listed below:

Table 3: Types of Mass Customization

Types of Mass Customization	Description
Transparent Customization	Companies offer individual products and services in a standard set to specific customers without notifying them that they are being customized. Companies achieve this by studying consumer habits and predicting their preferences over time without directly engaging with them.
Collaborative Customization	In this case, there are collaborative customizers who interact with customers to help them define their needs in order to create customized products following their guidelines.
Adaptive Customization	The company offers a standard product to customers with some personalization options. This guarantees that the product is developed in such a way that it can be customize, modify, or reconfigure by the end customer with ease.
Cosmetic Customization	It refers to the commercialization of standardized products and services in unique formats or packaging, according to the requirements of different customer segments. This means that customers have the choice to personalize the form, quantity, price and packaging of products that reflect their personality and style best.

Note: Adapted from “Mass Customization” by Wallstreetmojo & Vaidya, 2020, retrieved from <https://www.wallstreetmojo.com/mass-customization/>. And from “Mass Customization: What, Why, How, and Examples” by Luenendonk, M., 2019, retrieved from <https://www.cleverism.com/mass-customization-what-why-how/>

2.5.2. Implementation challenge

The transition from mass production to mass customization is enabled by the two following features of Industry 4.0: the Smart Factory and the 3D technology. As a matter of fact, it is necessary to manage Industry 4.0 technologies such as advanced robotics, big data processing, cloud computing, strong cybersecurity, IoT with smart sensors in order to implement the concept of mass customization in the company. Mastering 3D technology such as 3D printing (additive manufacturing), 3D visualization and 3D configuration (Augmented Reality) are also essential in order to prototype products on both the customer and producer side (Zhang, 2020).

The implementation of MC remains a huge challenge as manufacturers must be ready to effectively modify product variety, manufacturing processes and select the best solution according to different criteria (economy, quality). In order to be competitive, it is

absolutely necessary that the company is able to respond rapidly to the needs and requirements of the customers (this is a strategy commonly called Quick Response). This is made possible if the company has a flexible manufacturing system and the ability to design quickly (in terms of time), as well as to implement new products and processes of their manufacture. In Addition, given the diversity of customer needs, the applied scheduling methods need to take into consideration the possibility of producing products using various manufacturing resources. As a result, it is essential to incorporate scheduling into production planning processes (Zawadzki & Żywicki, 2016). In order to enable this flexibility in manufacturing, it is essential that machines in the production chain can interact with each other, collect data and issue instructions autonomously through sensors and sensors (IoT) and other Industry 4.0 technologies (Downey, 2021).

If the company is not sufficiently flexible, the products developed in a short period of time still have to wait their turn. If, on the other hand, the design is deficient (i.e. it takes too long), then the manufacturing process is not fully charged. In both situations, the delivery time to the customer is extended and may be unacceptable (Zawadzki & Żywicki, 2016). The other big hurdle to mass customization is the fact that most other companies are not necessarily flexible as well, their supply chains of most other companies cannot handle it effectively. Supplier systems are mostly optimized and built to produce a predetermined quantity of product instead of responding to any unexpected demand. the majority have not implemented the newest supply chain management applications such as just-in-time inventory and automated planning, resulting in less flexibility, specificity and visibility with regard to mass customization (Luenendonk, 2019).

One solution for companies to better manage their supply chain would be to make a compromise between mass customization and mass production to develop standard products and design them so that they can be personalized in the future. For the majority companies, the customization process is not economically feasible to start in the beginning of the supply chain (Luenendonk, 2019).

2.6. Critical success factors

There are 5 major challenges to consider when implementing Industry 4.0. These include huge costs, data security, lack of industry 4.0 skills and know-how, unreliable internet connectivity, and employee resistance to change. In order to overcome these challenges, it is necessary to consider the critical success factors (CSFs), which are factors that, once in place and understood in an organization, will lead to the successful implementation of an initiative (Sony & al., 2021).

2.6.1. Sufficient R&D resources

Industry 4.0 adoption often involves high upfront costs (NIBusinessInfo, 2019). To achieve Industry 4.0 implementation, a company's financial resources must be sufficiently available to meet requirements such as information acquisition, the cost of investing in the acquisition of key technologies (i.e., both software and hardware), and training and skill enhancement of the core workforce (Bongo & al., 2020).

Insufficient research and development spending can hinder the successful implementation of Industry 4.0, particularly in terms of the resources needed for Industry 4.0 operations. In addition to the resources needed to begin integrating key Industry 4.0 technologies, the expected costs of actually using these technologies must also be included in financial planning at the earliest stage (Bongo & al., 2020).

2.6.2. New business models

The common obstacle faced by companies adopting Industry 4.0 is the absence of internal alignment on the strategies to be pursued. The advent of digital technologies makes it essential to adapt or redesign the business model, by rethinking the way they operate (NIBusinessInfo, 2019). Success in Industry 4.0 starts with strategy design. Companies need to align Industry 4.0 initiatives with organizational strategy. These strategies can be short, medium and long term to ensure that the organizational strategy is followed. An estimated 70% of digital transformations have failed because, even if the technologies provide productivity, efficiency or greater customer management, if there is not a good internal strategy well implemented in the company, nothing will work (Sony & al., 2021). The implementation of Industry 4.0 modifies structures, procedures, working processes, job specifications, etc. in an organization. It is therefore essential to have effective change management as the implementation of Industry 4.0 is a radical change initiative. Change management moves need to be implemented systematically both within the organization and outside the organization (Sony & al., 2021).

The second major business model change is to align Industry 4.0 with your business differentiation abilities. Industry 4.0 is a key strategic opportunity to build long-term competitive advantage. Manufacturing organizations must have visibility into the few capabilities that differentiate them from the rest of the competition and align Industry 4.0 technology with these capabilities. The problem is that more than half of industrial companies are not clear on their differentiation capabilities. Being aligned with these abilities is not only about the digital maturity of the company in terms of products and services and supply chain, but also about other functions in the value chain, such as HR, tax, legal and compliance (Vassiliadis, 2015).

It is therefore important to have a clear value framework in order to build a viable business model based on Industry 4.0 technologies. This allows for a careful assessment of the potential risks and benefits, but also for a rebalancing and reprioritization of Industry 4.0 initiatives according to the actual value produced (Vassiliadis, 2015).

2.6.3. Workforce preparation

Employees will play an important role in the successful implementation of Industry 4.0. It will lead to an increase in human resource requirements, as conventional positions and roles will have to be changed significantly. This justifies management supporting the resources needed to manage the technology (Sony et al., 2021). With the paradigm shift comes a change in the required qualification of the workforce. Industry 4.0 involves interaction between individually complex core components (i.e. IoT, CPS, cloud computing or smart manufacturing). It is therefore necessary for the current workforce qualifications to adapt to this (Bongo & al., 2020). There will be a smart working environment for employees, with modified job descriptions, roles and responsibilities. Employees will require smart decision-making skills based on big data to handle business operations because of increased automation and integration of business processes (Sony et al., 2021).

The principal barrier to digital transformation is often identified as access to skills. Companies adopting technology report difficulties in finding, training and reskilling employees, especially in the fields of user interface, data science, software development and machine-level controls. Accessibility of technology is also sometimes an issue, with staff unwilling - or considering it too difficult - to operate new digital tools and software applications (NIBusinessInfo, 2019). Any successful transformation demands that all employees develop a high sense of purpose and mission for the change. (NAM News Room, 2021)

Companies need to prioritize and update the workforce. This requires a long-term view of the workforce and strategic planning. Adapting roles, recruitment and professional training to ensure that the workforce is prepared for the increased IT skills that will be expected (Rüßmann & al., 2015). Employees will need to be trained and re-skilled for the technological requirements of Industry 4.0. Demographic and social changes will also need to be taken into account to allow the workforce to manage its interconnected and autonomous interface (Bongo & al., 2020). Infrastructure and education will also need to be adjusted as producers adopt Industry 4.0 technologies. The way to address this issue is through a combined effort that includes government, industry associations and business (Rüßmann & al., 2015).

Managing culture adaptation is a key element of Industry 4.0 success, and a potential barrier if not well performed. If employees are unprepared for change, they are likely to

be reluctant, resistant or unable to adapt. Leadership and top management will play an essential role in achieving the cultural change required for digital transformation to ensure that employees are prepared for the technological change (NIBusinessInfo, 2019).

2.6.4. Data and IT security

By digitally transforming organizations and businesses, Industry 4.0 establishes a network of stakeholders such as the organization, customers and employees. The transparency of information and digital accessibility of information about various roles in organizations can expose them to cyber-attacks. The first major type of cyber-attack is the risk of privacy breach. In this case, hackers come and steal the company's data and attempt to use it for their own economic advantage. This is a major concern for healthcare and financial companies. The second type of cyber-attack concerns business continuity. This is the most critical cyber-attack risk for a manufacturing company. A shutdown of daily operations can be fatal to them (Miller, 2021). Cybersecurity management constitutes a significant component of the successful implementation of Industry 4.0 (Sony & al., 2021).

However, IT security is not just about cyber-attacks. Additional significant risks such as network configuration errors, erroneous commands and software or device failures can potentially disturb business operations and production. IT infrastructure must also be up to the task of dealing with the additional connectivity needed for digital transformation (NIBusinessInfo, 2019).

2.6.5. Understanding and receptiveness of new technologies

Companies implementing Industry 4.0 will need to be receptive and will have to accept the technology in order to digitize their supply chain and organization. Supply chains have to be a dynamic structure, this allows to meet the constantly changing needs of customers in terms of mass customization. Therefore, the success of Industry 4.0 depends on the collaborative efforts of the supply chain partners and the first step in this regard is to cooperate and digitize the supply chain (Sony & al., 2021).

It is essential that companies consider the full benefits of the technology (NAM News Room, 2021). As seen earlier, through various technologies, the digitalization of assets gives the organization the ability to detect and communicate diverse parameters of interest that will assist, through smart systems, in achieving the organization's goals. The objective for a successful Industry 4.0 implementation is that the products and services offered by the company must be smart (Sony & al., 2021). This also ensures that a considerable competitive advantage is maintained. By being able to acquire such a sophisticated technological infrastructure, organizations are assured of having sufficient

capacity to manage the day-to-day operations within a newly adopted innovation (Bongo & al., 2020).

Producers need to learn how to use technologies in new use cases to deliver the greatest benefits to their customers. In order to best develop their technology base, companies need to build the technological foundations, such as the tool base for analytics and develop their partnerships that will be essential in the digital world. Businesses should be also prepared for technological standardization and shape it through a long-term scenario-based vision of the sector and ensure that their strategy prepares them for the most probable scenarios (Rüßmann & al., 2015).

Organizations with previous experience of adopting new technologies will have a higher probability of success. As Industry 4.0 incorporates a combination of numerous and significantly complex technologies, the resulting changes in the typical operations and structure of the organization could become an overbearing managerial hurdle. In addition, as the pressure to keep a competitive advantage over other organizations rises, the successful deployment of a new technology may be negatively impacted due to incomplete planning and understanding of the technology's abilities and requirements (Bongo & al., 2020)

3. Case Adidas

For the past seven decades, adidas has been a leader in the sports equipment industry, influencing trends all over the world, as well as sport in general and the lifestyle of sportsmen and women. The brand has achieved great victories in both sports and business, while remaining true to the vision of its founder.

In 2016, they opened the first Speedfactory in Germany. The goal was to produce sneakers in a fully automated way, without human assistance, locally making themselves less dependent on their Asian supplier and using the principles of Industry 4.0.

3.1. The Speedfactories

The concept of the Speedfactory was born in 2015, Adidas wanted to create the factories of the future, a new way of working. The idea was to create sneakers only using automated robots. In 2015, the first Speedfactory was built in Ansbach, Germany (Guyot, 2015). To do so, they have concluded a partnership with Oechsler, a company that develops and produces parts for automotive, medical and industrial companies around the world and has been working with Adidas for a long time. Oechsler played a key role in the construction of the robots and production facilities installed in the approximately 4,600 square meter building (Bain, 2017). The two companies shared the costs to create this first plant, however neither company disclosed the precise amounts. Looking at the 2016 annual reports¹, Adidas' R&D spending increased from €139 million in 2015 to €164 million in 2016, with Speedfactory being part of this increase (see Appendix 2) (Adidas, 2016).

By September 2016, the first shoes from a Speedfactory arrived on the market. Named Futurecraft MFG, as in "Made for Germany", as they were exclusive to the country. This was a kind of public beta test of only 500 pairs. They had planned to produce 50,000 for the year 2017 (Adidas, 2016). Since then, Adidas has released pairs designed for London and Paris, the AM4LDN (see Figure 3) and AM4PAR, and more are on the way.

¹ Appendix 2: R&D ADIDAS 2016 ANNUAL REPORT



Figure 3: AM4LDN model by Adidas (retrieved from <https://stockx.com/fr-fr/adidas-speedfactory-am4-am4ldn-london>)

In 2017, Adidas opened a new Speedfactory in Atlanta in order to be closer and to provide faster delivery to the US consumer (Adidas, 2017). The adidas Speedfactory focused mainly on high-performance footwear such as the AM4 line, which was actually designed to be manufactured in the Speedfactory automated configuration. The shoes have only a few components and can be assembled in a minimal number of steps. Adidas expected the Ansbach and Atlanta factories to produce 500,000 pairs of sneakers each per year, representing 0.14% of Adidas' annual production: 360 million pairs (Cimino, 2019). Adidas has also in 2017 partnered with 3D printer manufacturer Carbon 3D to create their first series of sneakers using Digital Light Synthesis technology (Ayzenberg, 2017 ;3D natives, 2017). In 2018, Adidas produced more than 100,000 pairs of this high-performance shoes (Adidas, 2018).

In order to get a pair of shoes made at the Speedfactories, customers must first go to the Speedfactory Lab Experience to scan their feet to determine their exact length, width and position. Cameras record their stride, speed and gait while the customer runs on a treadmill. Adidas is then able to use this information to craft the perfect shoe in a short amount of time (Kim, 2018).

Unfortunately, Adidas announced in 2019 the closure of their 2 Speedfactories in Ansbach and Atlanta for April 2020. This will not mean abandoning the concept, but rather relocating to two of its suppliers in Asia. Adidas will also continue to collaborate with Oechsler and Carbon 3D (Chardennon, 2019).

3.2. Rationale for Speedfactories

The reasons which led Adidas to use Smart manufacturing instead of centralized production and therefore use Industry 4.0 technologies such as additive manufacturing or the Internet of Things are numerous.

The first reason given by Adidas in its 2016 annual report is that it brings production closer to the consumer, concluding that working locally has many benefits. It allows Adidas to move away from their dependence on Asian suppliers (although Adidas sourced 97% of its footwear in Asia in 2016) and it also greatly reduces delivery times. For example, previously, in one factory, the rubber was made, then the rubber was shaped into a certain form in another factory, the midsole was made in a separate location, and the midsole and bottom were joined together. It could take up to 60 days to make a shoe and even when the shoe was ready, it could take another 60 days to bring it to Western Europe or the US. In a Speedfactory, robot do most of the work and as a result, making a shoe was only a matter of a day's work (Bain, 2017; Adidas, 2016). Automation has also played a central role in the operation of Speedfactories, with robots replacing human labor to increase cost savings and efficiency (Hernández, 2020).

Proximity was also one of the main motivating factors in order to bring production closer to the world' s major markets. Most of Adidas' shoes are purchased in Asia, with production taking place in China, Cambodia, Laos and Vietnam. By automating a larger portion of their manufacturing cycle, Adidas will be able to produce closer to the place where their consumers live, even in high-wage countries such as Germany or the United States. Adidas will also track trends hidden in big data. This collection of all these data will involve a lot of IT and big data spending. The idea of speed at Adidas is not just about production, it is also about investing in technology to be able to react faster to consumer demand (Infor, 2016).

Another reason the company has given is that it will allow to open the doors to the creation of unique products that meet the functional needs and requirements of their consumers through the combination of footwear craftsmanship and cutting-edge technology. The objective of Adidas is to be able to manufacture custom-made shoes, where 3D printing is at the center of the process. If Adidas doesn't have to build the tooling for a sole, it suddenly becomes possible to customize a shoe to a customer's foot, design possibilities based on athlete data and high performance (Adidas, 2016).

Also, as Adidas wanted to be faster and more flexible, the automation of its production plant was the solution, bringing also more accuracy due to the advanced technology employed. Previously, to join 2 pieces the glue was used which was slow (because you had to wait for it to dry) and messy while now the pieces are mostly fused together. Speedfactory allowed to reduce the number of workers needed to design a shoe from 500 to 1000 in Asia to 160 in Ansbach which was composed almost of Oechsler employees. Adidas has always relied on low-cost manufacturing in Asia to maintain low production costs like other sportswear brands. Speedfactories were intended to substitute low-cost offshore labor with on-site robotic fabrication to lower costs. This shortens the distance

finished products must travel to reach Western consumers, leading to more efficient and environmentally friendly production cycles (Hernández, 2020).

By adopting advanced engineered techniques, like 3D printing, to reduce the manufacturing process to a couple of steps, Adidas can save on labor costs and decrease energy requirements and waste along the chain (Hernández, 2020). The Speedfactory network is designed to have a very low impact on the environment by limiting the carbon footprint (less transportation) and the use of certain materials (Runners, 2015). The use of the 3d printer allows a reduction of the waste generated. These new plants also reduce the risk of overbuying and reduce excess inventory levels (TOM, 2018).

In a nutshell, the 3 main reasons that pushed Adidas to launch their Speedfactories are speed of production and lead time, being closer to consumers and, meeting the need and expectation of consumer through their customization tools (Adidas, 2016).

3.3. Speedfactory components

By partnering with Oechsler, a company specialized in manufacturing automation, Adidas wanted to change the way of working and create the company of the future. We will see what a Speedfactory is composed of and what makes it so innovative by comparing it to the different technologies of Industry 4.0.

Internet of Things, Big Data and Blockchain

Adidas began working with SAP Leonardo in 2017, an IoT power company that helps them incorporate machine learning analytics and blockchain (Marek, 2017). This platform works well with running shoes that have soles and structure specifically tailored to an individual runner's stride and foot shape. This is made possible by technological advances in big data for running analysis and distributed manufacturing, with 3D printing of products in or around shops. The IoT enables these costs to be controlled, by efficiently tracking materials throughout the manufacturing process, which can be distributed across a series of dedicated manufacturing blocks. True connectivity and efficient processes enable the base of product parts to be available for shops to assemble with their own 3D printed soles (McGreal, 2017).

Adidas has layered machine learning with IoT sensors to supply chain systems that pass signals to central systems to create their Speedfactories (Gilchriest, 2018). The outcome is a massive amount of data stored and analyzed every millisecond. Using SAP Leonardo, Adidas uses this information in combination with machine learning to make evidence-based predictions of what will be needed, when and where (Marek, 2017).

Cyber-Physical System, Additive manufacturing and robotics

When opening their Speedfactories, Adidas decided to use cyber-physical production systems (CPPS) (Wahlster, 2016). The first device that can be associated with CPPS is a robot that works with the particle-foaming machine. It is supplied by Kuka, a robotics company. Industrial robots from Kuka are widely used in many sectors, including automotive manufacturers such as Tesla and Mercedes Benz. The Kuka robot is there to assist the Kurtz Ersa machine (see Figure 4). Indeed, as there is a lot of heat and heavy molds when the Kurtz Ersa produces the Futurecraft midsoles, the Kuka robot allows to safely retrieve the molded parts of the midsole (Solereview, 2017).

Then, there is a Kurtz Ersa, a particle-foaming machine that produces the Futurecraft midsole. It forms midsoles with BASF's expanded polyurethane compound (Infinergy e-TPU) which is a material that merges the properties of TPU with the benefits of foams, thus making it as flexible as rubber, but lighter and tougher. Adidas is the first company to use it to manufacture shoes. The fabrication of adidas Futurecraft foam is very similar to that of EPS (expanded polystyrene or commonly known as Styrofoam). In simple terms, EPS is the lightweight material that is often used for coffee mugs and thermal insulation. When heat is applied, the particle foam colony melts into the shape of the mold to combine to form a Futurecraft midsole (Solereview, 2017).

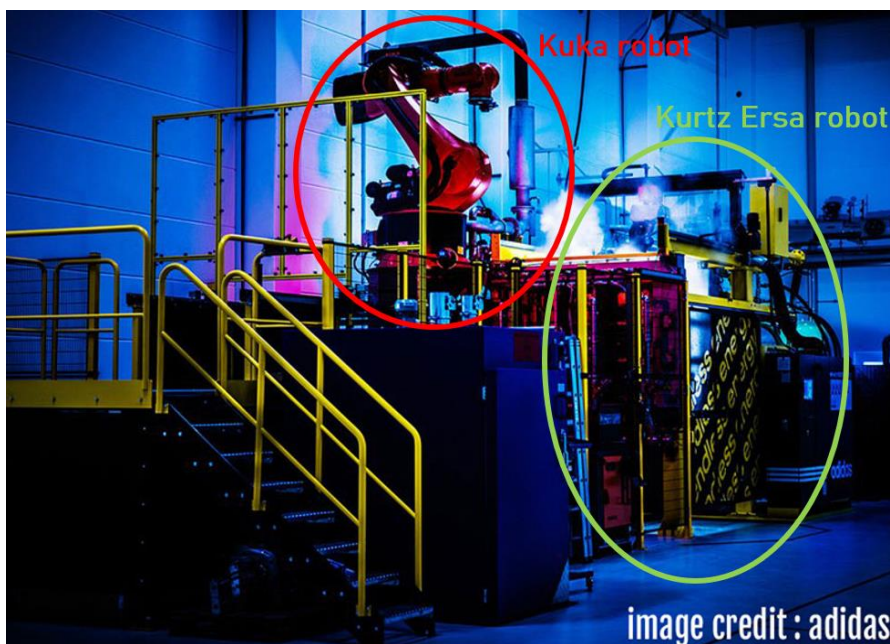


Figure 4: Kuka robot and Kurtz Ersa Robot in the Ansbach Speedfactory (Retrieved and Adapted from <https://www.solereview.com/whats-inside-the-adidas-speedfactory/>)

Thereafter, there is a knitting machine followed by laser cutting on the top of the knitted fabric. This process takes care of the upper part of the shoe called Primeknit which is a famous process at Adidas. The Primeknit is therefore sewn in one piece with a very

flexible and resistant weave, so there will be no stitching, which is an essential asset for athletes (Gentleman moderne, 2018). The computerized knitting machine used is a Stoll CMS 530 HP (see Figure 5), and the CO2 laser cutter is manufactured by Eurolaser (see Figure 6) (Solereview, 2017).



Figure 5: Stoll CMS 530 HP and Eurolaser (Retrieved from <https://www.solereview.com/whats-inside-the-adidas-speedfactory/>)

The next step seems to combine several steps. First, a rotary (and metal) cutter cuts the urethane (the material that will be glued to the flat part of the Primeknit) into a general shape, and then a laser will cut it into a specific shape. A Staubli TS-80 robot arm (Staubli is a company specialized in industrial robotics like Kuka) picks up these urethane strips and glues them onto the Primeknit flat component. The upper component then passes through a hot laminator which fuses the urethane strips to the fabric (Solereview, 2017). The Speedfactory is not all automated with machines or robots, there is a manual part. The upper part is sewn and then transported manually to a machine to mold the back part. It is this process that gives the heel buttress its curved shape. A stiffener is first attached to the upper with a light adhesive and then molded using this machine. Finally, someone mounts the upper on the last one and transfers it (this process seems to have been automated afterwards) to the only pressing station. The machine presses the upper onto the midsole and the shoe is finalized. All the processes that Adidas uses are not really new. What is innovative in the Speedfactory, on the other hand, is the sum of its parts. Most of the individual processes, be it laser cutting, knitting or robotic handling, have long been part of shoe and garment manufacturing. The manufacture of different types of footwear has been relatively automated for a long time, but of all footwear categories, the automation of the manufacture of cold-cemented, strobeled footwear (running shoes and its kind) is the most difficult (Solereview, 2017).

Later, when Adidas partnered with the digital manufacturing company Carbon 3D in 2017, the midsole was no longer crafted by the Kurtz Ersä machine but totally made via 3d printer and more specifically with the Digital Light Synthesis technology (see Figure

7). This device allows the development of functional prototypes and end-use parts on a single machine (Carbon, 2017).

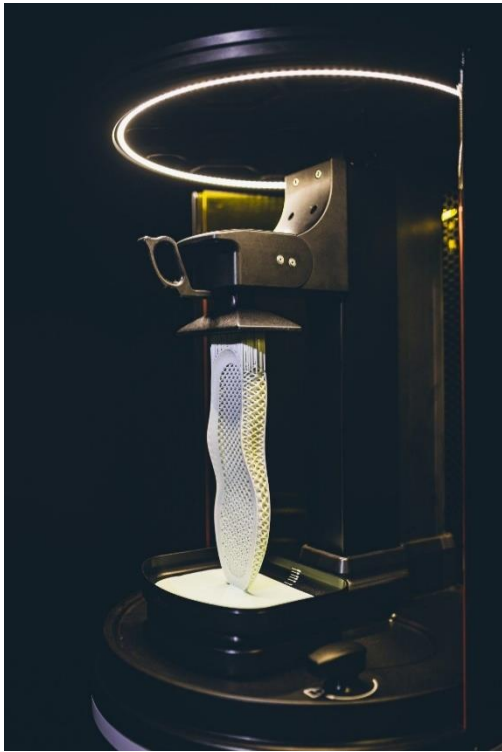
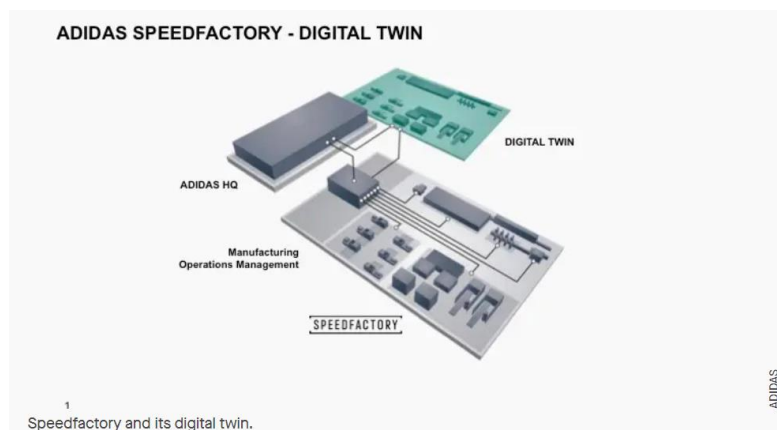


Figure 6: Digital Light Synthesis Printer (Carbon, 2017)

Augmented reality

In 2017, Adidas announced a collaboration with technology giant Siemens. Siemens will bring invaluable expertise in enriching the Speedfactory project by adding the virtual reality tool to the overall process. They will help Adidas create a "digital twin" of the SPEEDFACTORY (see figure 8) that will allow for upstream simulation, testing and optimization of the entire production process. Merging the virtual and real worlds will reduce time to market, provide greater flexibility, and improve manufacturing quality and efficiency (Gavrilovici, 2017).



¹
Speedfactory and its digital twin.

Figure 7: Digital twin of the Speedfactory (Bain, 2017)

In November 2019, Adidas partnered with Vyking, an AR testing technology company specializing in AR solutions for e-commerce and digital retail (Manalac, 2019). The company has launched a fitting tool in its iOS mobile application. The app follows the movements of your feet, allowing the virtual fitting experience to take place in real time, with or without shoes. The feature is linked to Adidas' Alphaedge 4D running shoe series, and allows users to virtually try on the trainers. Customers can visit any Alphaedge page in the app and turn on the AR feature by aiming the smartphone at their feet. An accurate image of the product will then be generated, scaled to the exact size of the user's foot (Streets, 2019).

Cloud computing

Adidas is leveraging a cloud-based platform to gain better end-to-end visibility into all inventory moves in its supply chain, starting from raw materials to final products. Using cloud technology, adidas can manage its transportation flows and integrate responsiveness and fast-mode principles into their manufacturing capabilities (Infor, 2016).

4. Analysis of the case

4.1. Comparative analysis between the Literature review and the Adidas case

4.1.1. The 6 principles of Industry 4.0

In this section, we will compare the 6 principles of Industry 4.0 (cf. 2.2) with the strategy employed by Adidas in their Speedfactories:

Table 3. The six principles of Industry 4.0

Principle	Description
Interoperability:	Cyber-physical systems make it possible for people and Smart Factories to communicate and connect with each other.
Virtualization:	By connecting sensor data from cyber-physical systems to virtual shop floor models and simulation models, a virtual copy of the smart factory is created.
Real-time capability:	Data is gathered, analyzed and immediately converted into insights.
Decentralization:	Cyber-physical systems are capable of making autonomous choices and producing locally.
Service orientation:	All cyber-physical systems and human services are provided internally or even outside the company.
Modularity:	Smart factories are highly flexible and can accommodate changing needs by replacing or extending individual modules.

Note: Adapted from “Industry 4.0: A survey on technologies, applications and open research issues” by Lu, Y., 2017, *Journal of Industrial Information Integration*. And from “Design Principles for Industrie 4.0 Scenarios: A Literature Review” Hermann, M., Pentek, T., & Otto, B., 2015, *Technische Universität Dortmund*.

Interoperability

Adidas' premise was to turn the Speedfactories into Smart Factories. Automation would play a central role in the operation of Speed Factories, with robots replacing human workers to decrease cost and increase efficiency (Hernández, 2020). Their goal was to be able to set up small and fully automated production hubs around the world, where shoes can be manufactured and dispatched in a fraction of the previous production time (Henkel, 2016). However, in reality, the Factory was not fully automated, with some precision work still being done by humans (SV, 2017).

Adidas was thus divided between technology and human capital. Achieving full automation turned out to be an impossible endeavor. Shoe soles are printed by use of 3D

machines using new materials such as mesh or recycled plastics. The upper knit was first designed virtually and then produced automatically. Then, the two elements needed to be combined by workers who performed the gluing and molding phases (Bellotto, 2020).

We can therefore conclude that the principle of interoperability was not fully and efficiently achieved by Adidas.

Virtualization

Adidas allows their consumers to photograph their feet in the store with a specialized device, in order to choose the shoe online from home and specify their preferences (shapes, colors). All this information was forwarded to production (L'usine nouvelle, 2019). With the product design ready, manufacturers and resource providers simply receive the scan file from the product designers, print it with a commercial 3D printer and test it. If an enhancement or change is required, manufacturers can simply modify the product design in the program and send the file back to the product designer (Young, 2017).

The virtualization principle has been properly applied by Adidas to their Speedfactories.

Real-time capability

Speed is an integral part of Adidas's strategy. Adidas has named the project "Speed Factory" to address this "need for speed" in manufacturing and production time. Their goal is to be able to respond to any request quickly. The objective in creating Speedfactories was, among other things, to get closer to the customer in order to provide them with the opportunity to react to demand in real time (Adidas, 2017). Digital technology allows them to make faster product decisions, improve collaboration between creative functions and their suppliers, and to reduce abandonment rates (Adidas, 2016).

The traditional prototyping process involves raw material suppliers and manufacturers physically seeing the product, trying it on and sending it back to Adidas. When further modifications are needed, as is often the case, this process inevitably becomes longer. In contrast, this can be reduced in Speedfactories thanks to the integration of design and 3D printing programs. In addition, Speedfactories enable robots to take on time-consuming tasks and significantly decrease downtime in factories, often due to the reprogramming and retooling of machines required by product line changes (Bullard, 2017; Young, 2017). It takes up to 60 days to manufacture a shoe for Adidas in traditional production and 60 days to bring it to Western Europe or the United States. In a Speedfactory, robots do most of the work and therefore, manufacturing a shoe can take as little as a day (Bain, 2017).

Based on the way Adidas has reduced lead time with their Speedfactories, we can deduce that they have properly applied the principle of real-time capability.

Decentralization

Speedfactories were decentralized and thus utilized decentralized assembly, using smart manufacturing instead of centralized production (Adidas, 2016; Henkel, 2016). The Speedfactories functioned as part of Adidas's global strategy to decentralize manufacturing and distribute operations amidst persistent supply chain scarcity. Like most sportswear brands, Adidas has typically depended on low-cost manufacturing in Asia to maintain low production costs. Speedfactories were intended to substitute low-cost offshore labor with on-site robotic manufacturing to reduce costs. This reduces the mileage that final products had to travel to reach Western consumers, turning production cycles more efficient and environmentally friendly (Hernández, 2017).

As a result, Adidas has effectively decentralized their Speedfactories.

Service orientation

The digital twin of Speedfactories created by Siemens simulates, tests, and optimizes the entire production process upstream and thus brings greater flexibility to the services offered. By digitizing the value chain, Adidas can implement new technological developments more rapidly, use available resources more efficiently and transparently and thus react more flexibly to the individual needs of our consumers - to give them what they want when they want it (Gavrilovici, 2017).

Adidas therefore has a strong position in terms of the service it offers their customers.

Modularity

In the case of Adidas, the focus is no longer on products but on customers, and mass production is replaced by personalized services. In accordance with customers' growing desire for individualized products and their aversion to long lead times, the new system allows for mass customization and the capacity to react flexibly to changes in demand (MFXR, 2017).

In addition, the use of robots, machines and 3D printers instead of human workers enables the Speedfactory to quickly adjust to product and manufacturing process changes. For example, in a conventional Adidas production plant, the facility must be shut down for a few days if it intends to switch from Model A to Model B, as the machines must be rescheduled and retooled. In contrast, in an automated environment, where there are fewer manual processes and the machines are controlled by user-friendly interfaces, the facility can shift from producing one product to another almost instantly (Young, 2017).

We can consider that the Speedfactory adequately applied the principle of modularity.

4.1.2. The Mass Customization Made by Adidas

We will compare how Adidas has implemented mass customization through their Speedfactories based on the literature examined in chapter 2.5.

As mentioned earlier, the transition from mass production to mass customization is enabled by two features of Industry 4.0: the 3D technology and the Smart Factory.

Regarding the 3D technology, Adidas has mastered it. In terms of additive management, Adidas has first partnered with Kurtz Ersa and their particle-foaming machine, and then with Carbon 3D, the digital manufacturing company that provided them with the Carbon Digital Light Synthesis. Adidas' Future Team, the group tasked with the development of solutions for disruptive change in a 2–5-year time span, has identified 3D printing as a possible technological solution in order to offer mass customization, and has therefore invested significantly in multiple additive technologies (Smith, 2019).

This explains their collaboration with Siemens to create a digital twin of their Speedfactories in order to stream simulation, testing and optimization of the entire production process. Adidas also collaborated with Vyking to optimize their iOS mobile application, which allowed customers to have virtual fittings by simply filming their feet.

Because of this flexibility, Adidas does not require standardization of footwear components, particularly injection-molded insoles, and can instead allow customers to make significant design changes to parts of their products that were beyond the reach of customization (Smith, 2019).

In addition, Adidas has understood that one of the challenges of mass customization is the ability to design quickly, by reducing the design time from several months to a few days.

Nevertheless, there are limits to the 3D printing process, specifically for high-performance athletic footwear such as material durability and longevity of components, as well as the capacity to scale up production based on planned production runs for Adidas products. Adidas manufactured 402 million pairs of shoes in 2017. The most optimistic forecast for the Futurecraft line of 3D printed shoes was a few hundred thousand, or less than 0.3% of total unit production. Therefore, 3D printing, in theory, can allow for customization, but a shared barrier to making mass customization viable is scalability (Smith, 2019).

As for the Smart Factory, Adidas has understood the need to master all relevant technology. However, they still need human intervention as the upper knit and the sole have to be assembled by human workers. This results in breaking the initial "goal" of the Smart Factory interoperability principles. The main problem here is the impossibility of

achieving full automation and involves the use of human labor. The Adidas production process is therefore divided between technology and human capital (Smith, 2019).

Concerning mass customization implemented by Adidas, we can conclude that they have mastered the 3D part of mass customization features. However, there was a problem in the Smart factory feature of the mass customization. Adidas has not been able to fully automate their production processes, which meant that they needed to resort to human labor.

4.1.3. Does adidas meet the success factors?

4.1.3.1. Sufficient R&D resources

Adidas did not disclose how much they invested in the construction of Speedfactories. Some of the costs were shared Oechsler, with whom they entertain a partnership. The costs of Speedfactories are included in Adidas's R&D budget (Bain, 2017). They have spent 149 million on R&D in 2016 (10 million more than in 2015), 187 million in 2017, and 153 million in 2018. Adidas' average yearly R&D expenditure from 2015 to 2019 is €156 million and this represents 0.8% of total net sales (Adidas, 2019).

R&D expenses from 2015 and 2019 (Adidas, 2019):

Table 4. Research and development spending of Adidas from 2015 to 2019.

	Average (2015 – 2019)	2019	2018	2017	2016	2015
R&D expenses (€ in millions)	156	152	153	187	149	139
R&D expenses (in % of net sales)	0.8	0.6	0.7	0.9	0.8	0.8
Net sales (€ in millions)	20,434	23,640	21,915	21,218	18,483	16,915

Note: Adapted from the 2019 Adidas annual report.

We compared these figures to the 2015-2019 R&D expenditures of big sneaker brands such as Nike, Asics and Puma (see appendix 3):

Table 5. Average research and development spending by Asics, Puma and Nike from 2015 to 2019.

	Average from 2015 to 2019		
	Asics	Puma	Nike
R&D expenses (€ in millions)	31	56	500
R&D expenses (in % of net sales)	1.0	1.3	1.3
Net sales (€ in millions)	3,083	4,260	38,330

Note: Adapted from the 2019 Annual report of Asics and puma and from Denis Green's article about Nike's R&D spending estimated by Morgan Stanley: <https://www.businessinsider.com/morgan-stanley-note-on-adidas-nike-2017-6?IR=T>

When we compare the percentage of R&D expenditure to net sales of Adidas with the other 3 brands. We notice that Adidas is more efficient in its R&D spending as its percentage (0.8%) is lower than the other three brands (1.3%, 1.0% and 1.3%).

We believe that Adidas had sufficient research and development assets and invested adequately in the Speedfactories to ensure a successful outcome.

4.1.3.2. New business model

In their business model, Adidas focuses mainly on production speed, geographical proximity to their customers, and customization, rather than all the problems that could arise simultaneously. Their sales and distribution strategies are almost solely based on speed. This is their strategic priority, which they put in motion with disruptive business models, like Speedfactories (Adidas, 2017). As the name indicates, a Speedfactory aims to manufacture Adidas merchandise more quickly than their competitors. They chose to relocate to Germany and Atlanta primarily because they were closer to their customers and could thus increase efficiency. The company boasted an essential benefit in a context where fashion cycles are faster than ever (Bain, 2017).

Two factors were not sufficiently considered in Adidas' business plan: customization and localization.

Originally, the project was to focus on mass customization to provide different shoes for different customers. Adidas wanted to introduce laboratories around the world where athletes could test and send their personal data to the machines and thus fully customize their sports shoes. It all began with the consumer in front of the analysis, the collected data had to be elaborated and then the processes of production using the new equipment had to start. However, the concept faded away in a short time, and the idea of mass customization was contained to the initial stage. As a result, the market had received a new line of footwear designed in an innovative way, nothing more. Nowadays, consumers are demanding more and more features and flexibility in athletic or sports footwear. Brands that consider closely the end use of their product and tailor it to comfort, versatility and accessibility will be more successful in convincing a wider market (McDonald, 2019; Euromonitor, 2020). The embracement of 3D printing technology is driving the demand for the custom footwear market (Expert Market Research, 2021). Another important factor when buying shoes is price. Younger customers prioritize price and fashionable style over quality aspects (Pospisilova, 2013). However, expensive product costs and limited customization are barriers to market growth. Actors have to offer greater levels of personalization to attract more customers (Goldstein Research, 2020). At present, the Adidas AM4 manufactured in the Speedfactories are available online, but there is no indication of the possibility to personalize them (Bellotto, 2020).

One of Adidas's shortcomings was their insistence on establishing their manufacturing sites in the largest market cities. The salient advantages in bringing production closer to the consumer are that they become more responsive to regional and short-term product trends, as well as supply chain compression. In practice, however, the attraction of such locations can be treacherous. These advantages must outweigh costs such as duplication of capital and plant, higher paid labor, and removal of economies of scale, in order to be profitable. In this equation, despite all the customization and enhanced capabilities that 3D printing offers, producing athletic shoes locally to shorten lead times was not a significant enough value proposition to justify the cost of infrastructure, technology, organizational management, and labor required (Smith, 2017).

In our opinion, Adidas has failed to complete this success factor. Although the speed of production provided by Adidas was efficient, the localization and customization features proposed by Adidas largely hindered the project.

4.1.3.3. Workforce preparation

Adidas examines the risks related to organizational structure and their innovative strategy very carefully and therefore relies heavily on their HR department. They employ internal and external experts in project management as frequent organizational changes can lead to fatigue and misunderstandings between staff members and thus reduced efficiency and productivity. They educate, support and engage the workforce to embrace new processes continuously (Adidas, 2016).

Adidas' human resources strategy aims to foster a corporate culture based on trust, creativity and collaboration (Adidas, 2016). They do not talk about implementing an Industry 4.0 culture. However, we do not believe that this is one of the factors that led to the failure of the Speedfactories.

4.1.3.4. Data and IT security

The most dangerous risk for Speedfactories would be a cyber-attack that would affect their business continuity. An interruption in the operations of an automated company can be fatal.

To minimize cyber risks, Adidas proactively engages in preventive network maintenance, service continuity scheduling and compliance with applicable IT policies. Information security is handled by limiting user access according to position description and by complying with data security guidelines. They perform frequent security reviews of key systems and applications and have monitoring and warning procedures in place to identify and properly address IT security incidents. Extra security precautions, such as anti-virus software and firewalls, are intended to enhance the protection of critical

systems and information. They also conduct numerous daily backups in alternative data centers for the company's central ERP system. Moreover, the backup solution for the ERP system allows them to rapidly move to a distant site if required without any drop in data. The security control and reliability of the system are routinely inspected and checked by the internal audit department. To make employees aware of information security and data privacy, they organize different training programs and periodic information campaigns (Adidas, 2016; Adidas, 2018).

By looking at the steps taken by Adidas to counter cyber-attacks, we can assume that they fully understand the risks related to cyber security.

4.1.3.5. Understanding and receptiveness of new technologies

Ostensibly, Adidas has thoroughly considered the full benefits of technology when it comes to their partnerships. Technological advances are occurring at an unprecedented rate and are having a profound impact on Adidas business. They have always aimed for the most innovative solutions (Adidas, 2018). By working with Oechsler, the leading automation company, they have made considerable progress towards digitizing and networking an almost fully automated production process (Smith, 2017). They have collaborated with SAP Leonardo for machine learning analytics and blockchain, Kuka for robotics to assist with the particle-foaming machine Kurtz Ersä. They also solicited Carbon 3D for their Digital Light Synthesis technology, as well as Siemens to make the digital twins of the Speedfactories. Finally, they also cooperated with Vyking to optimize their augmented reality application.

Additionally, they have put in place a substantial infrastructure to accommodate this new technology with an approximately 4,600 square meter building and 160 employees at the Ansbach location to ensure sufficient capacity to manage day-to-day operations (Bain, 2017).

However, as seen in the chapter 2.6.5, it is important for a company to master its technology to increase their chances of success in Industry 4.0. Adidas does not have much experience in adopting new technologies because they outsource all their know-how to Asia until their Speedfactories project. They externalized 97% of their footwear know-how related to production processes to Asia until 2016 (Bain, 2017).

We can conclude that Adidas has understood and embraced the new 4.0 technology. Nevertheless, they were obliged to engage in many costly partnerships as they were sorely lacking in know-how. In our opinion, the success factor is not reached by Adidas. In certain extent it is achieved, because they understood the importance of acquiring the new technology. But they were not able to manage it themselves.

4.1.4. Why did the Speedfactories “fail”?

From the above analysis, we can identify 4 main factors that made Speedfactories fail: impossible interoperability, lack of know-how, localization and customization.

The first reason why adidas Speedfactories failed is the impossibility to turn the totality of the Speedfactories into Smart factories. Total automation was impossible and human help has to be employed in the process when combining gluing and molding the sole and the upper knit. The need of human labor would not have been a problem if the Speedfactories had been located in Asia since it is economically feasible environment. It is mainly for the economic reason that 97% of Adidas products are manufactured in low-wage place such as Asia.

To make the same products in higher-wage economies, a larger labor force is simply not economically feasible in most cases (Smith, 2019). The German and North American landscape did not offer the necessary manpower for a company like Adidas. The costs were not sustainable, or better yet, compared to the Asian market, they were higher (Bellotto, 2020).

The second main reason is Adidas' lack of know-how. Until they launched the Speedfactories, they were outsourcing 97% of their production to Asia and thus, 97% of know-how (Bain, 2017). This lack of know-how resulted in increased costs due to the numerous partnerships made. The implementation of new production lines in Germany and the USA proved to be impossible due to the lack of know-how and the limited availability of raw materials (Ross, 2020; Bellotto, 2020).

As we noted, the problem of interoperability and know-how would not have arisen if Adidas had chosen a low-wage location. The main obstacle they faced was high costs due to their choice to be closer to their customers and away from Asian dependency. Their choice of location was the major factor in their failure when it was expected to be their strength in getting their product to customers faster. This choice of location along with their 2 concerns related to interoperability and know-how significantly increased their costs as they had to employ workers and enter into costly partnerships.

The last element that made the Speedfactories fail was the fact that they rapidly abandoned the customization aspect they initially offered. As a matter of fact, it was no longer interesting for the customer to have standardized shoes simply because they had been designed in an innovative way via cutting-edge technology such as additive management in smart factories. We can therefore assume that the way the shoes are made does not interest the customer if it has no impact on the price or the product. In this case, they had to pay more for standard shoes because they were made in an innovative way.

The consumer expects to be part of the innovation flow, and soon enough, they only have the option of buying a non-customizable pair of shoes on the Adidas website (Bain, 2017).

However, this "failure" is not considered as such by Adidas. They did not actually pursue the idea of completely replacing its mass production sites in China, Vietnam and Indonesia with Speedfactories in Germany. Contrary to what has been said in public media, Speedfactories were not a case of Adidas shifting its sourcing strategies from Asia to Germany, but instead an attempt to supplement the Asia-centric production system with an additional exclusive product facility (Butollo, 2020). To offer an alternative perspective, its relocation to its Asian supply base was a strategically sound decision. Ultimately, Speedfactories were a supply chain success misinterpreted as a public relations failure. Over its three-year life-span, the Speedfactories program has helped Adidas understand how digital technologies, including 3D printing, can change the shape of its supply chain over the next decade. The future of footwear manufacturing is now closer to Adidas, according to Gerd Manz, vice president of technology innovation at Adidas (Smith, 2019).

4.2. Analysis of the Asian relocation

In 2019, Adidas decided to relocate their Speedfactories and shift its focus on production in their factories in Asia, particularly in China and Vietnam (Mathur, 2019). The primary reasons for relocating Speedfactories to Asia was that the factories will be more economical and flexible (Thomasson & Reuters, 2019). Adidas expects to be able to deploy some of the Speedfactory technologies in their Asian facilities for improved utilization of available manufacturing capacity (Mathur, 2019). According to Adidas, they consider the fastest and most cost-effective way to get a return on investment to bring Speedfactory technologies to their manufacturing base in Asia (Smith, 2019). Adidas is not abandoning 3D printing technology as a superior way to manufacture footwear, but it shows that where the technology is located still matters at the bottom line. With the shift in production, Adidas suggests that the business case is still stronger in Asia, even with advanced technology and regardless of the proximity of targeted consumers (Cosgrove, 2019).

By pioneering Industry 4.0 with Speedfactories, Adidas realized that taking the local approach was not the most cost-effective way to scale product and process innovation. Speedfactories have been critical in deepening innovation and production capabilities. This was their objective from the beginning as they are now well-positioned to combine this newly acquired expertise with other advances made with their suppliers, while simultaneously extending the range of products available (Smith, 2019).

By relocating to Asia, Adidas will focus on strengthening its established and expansive supply chain and focus on that bottom line. The Adidas Future Team is confident that they

have put the company in a powerful position to be disruptive to the market in the foreseeable future, having expanded the ability to provide a customizable experience beyond what their competitors can achieve and what consumers expect (Smith, 2019). They will also continue to work with their main partner Oechsler (Thomasson & Reuters, 2019).

This "failure" of Adidas can be a lesson for the rest of the manufacturing industry, not to give up repatriating manufacturing plants, but rather to think about the process itself first (Hernández, 2020). The company also plans to expand their Speedfactories technology beyond the footwear category at its new facility (Cosgrove, 2019).

Relocating its automated production to Asia, however, carries risks. By increasing the volume of shoes as well as the number of SKUs (Stock Keeping Units) through lower production costs, Adidas could end up moving away from what consumers want. They also run the risk of overproducing items that are not sufficiently customized or meaningful to consumers in their home market, at a time in which technology has pushed people to expect products that are specific to them. In addition to the loss of autonomy, Adidas could also reclaim stronger technology in the future by disconnecting from innovative and experienced companies working in Europe and the United States (Towers-Clark, 2019). Therefore, Adidas must keep their core objectives in mind.

5. Conclusion

Industry 4.0 has become virtually ubiquitous in our time. Manufacturing companies perceive considerable advantages, both economically and operationally. Industry 4.0 is the new concept that will revolutionize the world of production, and much more. With the possibility of interconnectivity and digitalization of the environment, this concept will bring production to the next level by enabling, for example, mass customization.

The objective of this thesis was to have a critical look at the viability of Industry 4.0, or the 4th industrial revolution, outside of Asia. To address this issue and find a research question, we chose to take a particular case which was the case of Adidas' Speedfactories. Launched in 2015 with the aim of being closer to their customer and offering a new service to customize their athletic shoes, Adidas closed Speedfactories in 2019. We therefore studied the reasons that pushed Adidas to relocate them to Asia, where 97% of their production were located.

Throughout this thesis, we have attempted to explain as clearly as possible what Industry 4.0 is and what it represents for the industry. In the literature review, we have covered all the features of Industry 4.0 as well as the different principles and possibilities that arise from it. We also listed the different success factors for a successful implementation of Industry 4.0. Then, we presented the case of the Speedfactories by giving the reasons that pushed Adidas to launch them and the technologies involved. In the last chapter, we compared the literature review to the case to determine the reasons of the failure of Speedfactories.

The first reason is the impossibility of interoperability of Speedfactories - Adidas could not fully automate their Speedfactories. This resulted in a need for workers that would not have been a problem in Asia. In Europe, however, wages are much higher, which was not economically feasible. The second issue faced by Adidas was the lack of know-how. As they outsourced 97% of their production to Asia, they had no knowledge of the adopted technology and were compelled to engage in costly partnerships. The last reason is the customization of the footwear implemented by Adidas. At the dawn of Speedfactories, customers recognized the added value that customization brought with it. However, the option to customize was quickly discontinued by Adidas, which resulted in the return of standardization of the merchandise. Customers no longer saw the value of buying shoes from Speedfactories, in particular, as the higher price did not justify the minimal differences in comparison to ordinary retail products.

Adidas was a fitting case study for showcasing the intricacies of Industry 4.0 viability outside of Asia. Their strategy of implementing Industry 4.0 factories in Europe (Ansbach) and in the US (Atlanta) was an attempt to prove that independence from low prices and expertise in Asia could be possible. The lack of this expertise contributed to the failure

that ensued. However, what they have accomplished is impressive from a production innovation point of view. They are the first to try to do this on this scale. Adidas does not consider this operation a failure; they have learned a lot from this "mistake" in terms of production and technical innovation. They simply relocated their Speedfactories to Asia to make the best use of the technology and know-how available there.

To come back to the initial research question concerning the viability of starting in Industry 4.0 outside Asia for a production company, we can say that it is indeed possible to succeed but under constraint of several factors. First of all, it is important to master the technology that the company intends to acquire. It is interesting and important to establish partnerships, but it is necessary to be careful with the number of partnerships that can be costly. Secondly, it is imperative to understand industry 4.0 as a whole. Making a smart factory is very interesting but very expensive, if it is not fully automated and too much human input is required, it will take away the entire principle of the smart factory by significantly increasing the costs. Manufacturing companies interested in moving into Industry 4.0 must consider that a local approach is not the most cost-effective way to expand product and process innovation. Corporate culture, although it was not a factor in the failure of the Speedfactories, is also very important. Introducing new technology in a company may not be accepted or understood by the staff. Education and training must be implemented soon.

This thesis has raised the question if Adidas did not act prematurely with Speedfactories. People may not have been ready for this technology and perhaps did not yet understand its value. This work may prove useful in a future attempt to study Adidas (or another organization) potentially implementing a fully autonomous Smart Factory of this scale in Europe or outside Asia. A Wavestone study conducted in 2020 informs us that a growing number of companies are investing in digital. Nonetheless, this study demonstrates that 75% of the companies surveyed are not yet planning a major relocation to Europe (Wavestone, 2020). A change may occur in a few years, and then it is possible that the production processes will become automated as close to the consumer as possible.

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7. Appendix

Appendix 1: CSF of Industry 4.0

CSF 1: An empirical examination of benefits, challenges, and critical success factors of industry 4.0 in manufacturing and service sector (Sony & al., 2021)
1. Aligning the Industry 4.0 initiatives with organizational strategy.
2. Top management shall support the Industry 4.0 initiatives.
3. Employees will be important for the success of Industry 4.0
4. Make your products or services smart
5. Make efforts to digitize the supply chain.
6. Digitise the organization.
7. Change management.
8. Project management.
9. Managing cybersecurity
10. Operational, economic, environmental, and social sustainability of Industry 4.0.
CSF 2: Industry 4.0: What it means for your business (NIBusinessInfo, 2019)
1. Lack of skills
2. Data and IT security
3. New business models
4. Culture change
5. Capital investment
6. Help with Industry 4.0 implementation
CSF 3: Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries (Rüßmann & al., 2015)
1. Producers must set priorities and upgrade the workforce
2. Suppliers must leverage technologies
3. Infrastructure and education must be adapted (rubman & al.,)
CSF 4: Critical success factors in implementing Industry 4.0 from an organisational point of view: a literature analysis (Bongo & al., 2020)
1. Highly qualified workforce
2. Availability of required infrastructure
3. Receptiveness to the new technology
4. Financial support
5. Strong enforcement of intellectual property rights
6. Self-regulating framework

7. Complexity management
CSF 5: The Six Factors of Manufacturing 4.0 Success (NAM News Room, 2021)
1. Technology Adoption
2. Data-Driven Decision Making
3. New Business Models
4. Innovation and Experimentation
5. Well-Integrated Teams
6. Culture
CSF 6: Industry 4.0: what are the key success factors to become a digital factory? (PWC, 2020)
1. Develop a Proof of Concept to validate the technology and to strengthen trust towards the solution and the positive impacts of industry 4.0.
2. Define a clear roadmap, aligned with its digital strategy.
3. Involve the team, and all the people from the organisation, from the start.
4. Develop collaboration to support the internal R&D team to unlock the value of the technologies
CSF 7: Six key success factors to create value with Industry 4.0 (Vassiliadis, 2015)
1. Align Industry 4.0 to your company's differentiating capabilities
2. Have a clear value framework
3. Build a leading change coalition
4. Validate the Target Operating Model
5. Go cross-functional
6. Ensure ability to execute

Appendix 2: R&D ADIDAS 2016 ANNUAL REPORT

	2016	2015	2014	2013	2012
R&D expenses (€ in millions)	164	139	126	124	128

Appendix 3:

Puma

	Average (2015 - 2019)	2019	2018	2017	2016	2015
R&D expenses (€ in millions)	55,54	61,7	54	53	52	57
R&D expenses (in % of net sales)	1,3	1,1	1,2	1,3	1,4	1,7
Net sales (€ in millions)	4260	5502	4648	4135	3626	3387

Asics

	Average (2015 - 2019)	2019	2018	2017	2016	2015
R&D expenses (€ in millions)	31	35	34	34	28	24
R&D expenses (in % of net sales)	1,0	1,2	1,1	1,1	0,9	0,7
Net sales (€ in millions)	3083	2925	2991	3096	3088	3315

Nike

	Average (2015 - 2019)	2019	2018	2017	2016	2015
R&D expenses (€ in millions)	500	500	500	500	500	500
R&D expenses (in % of net sales)	1,3	1,1	1,3	1,3	1,4	1,5
Net sales (€ in millions)	38330	44493	37420	39122	36363	34254