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EXECUTIVE REPORT ON THE ROLE OF ENABLING TECHNOLOGIES FOR INDUSTRY 4.0

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EINST4INE

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EXECUTIVE SUMMARY

Industry 4.0 marks the fourth industrial revolution in manufacturing. This is a Cyber-physical systems revolution that augments the physical production lines with sensors and actuators that allow data gathering and digital controlling of the production. Doing so increases the flexibility of production plants, allowing mass customisation, i.e. customised products at a mass production scale. Furthermore, resources, including production assets and raw materials, can be used more efficiently. Many technologies contribute to this vision of the manufacturing of the future. While some technologies rely on advancements of proven technologies such as robots and IT infrastructure, others fundamentally change supply chain interactions and plant coordination. The technologies include: **Cyber-physical systems**, fusing the digital controlling with physical machines, **internet of things**, enabling real time sharing and accessing of data from devices, sensors and products, **5G,** providing the infrastructure for communication of significant amounts of data with low latency, **Big Data,** collecting massive datasets which can be used for sophisticated tools to improve performance, **simulation** of processes and supply chains for better planning, evaluation and controlling, **cloud computing,** sharing computing resources in a network of devices**, advanced robots,** adding flexibility to robots and increasing their range of application, **artificial intelligence,** using data to aid in decision making and product designing processes, **augmented reality**, visualizing data conveniently to assist operators, **additive manufacturing,** a new way of creating parts layer by layer which allows the creation of complex geometries and **blockchain,** providing a transparent, distributed and secure infrastructure for data exchange.

The concept of industry 4.0 is ever-evolving with new (and unexpected) possibilities due to the interactions of the technologies mentioned above and the emergence of other technologies. Undoubtedly, the concept has now been partially realised, yet leaving substantial potential for significant change in manufacturing. However, as experienced during the last decade, this transition comes at the expense of added complexity. Hence intercompany interactions within and across traditional industries can no longer be fully understood using the traditional supply chain view but instead call for an ecosystem perspective.

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WHAT IS INDUSTRY 4.0?

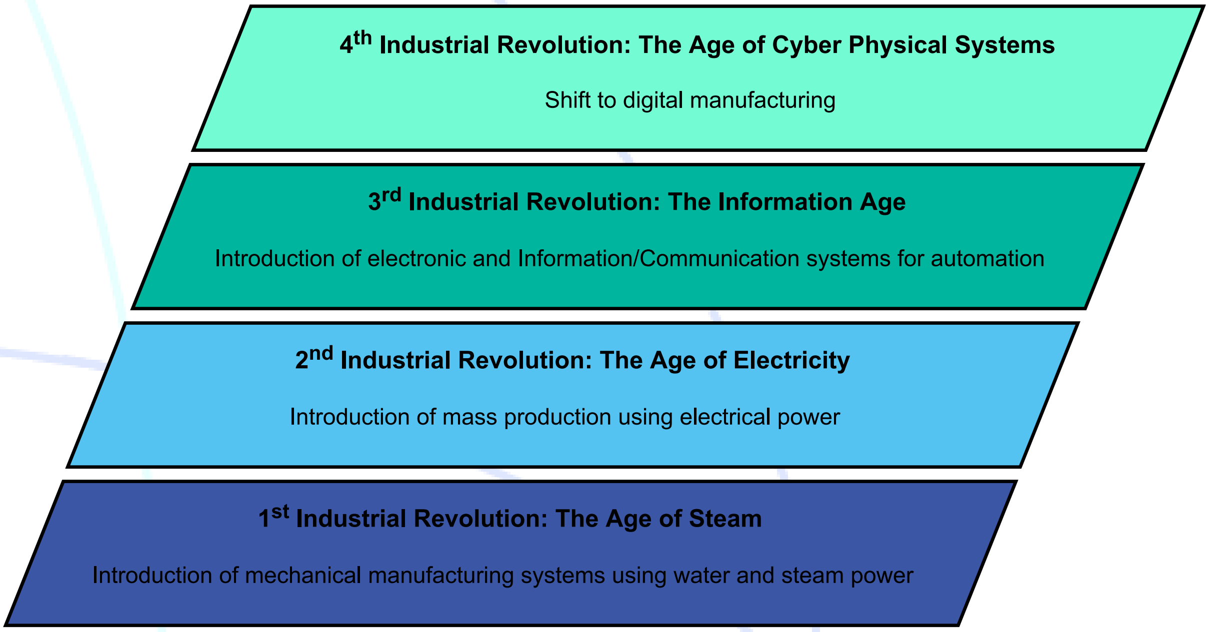

Figure 1: Industrial revolutions adapted from Xu, Xu and Li, 2018.

The manufacturing industry is ever-evolving and has undergone significant changes throughout the last centuries. At the end of the eighteenth century, the first mechanical manufacturing systems started to steer the industry towards automatisation in the first industrial revolution. The introduction of electricity significantly improved the scalability and flexibility of automated processes, which previously were powered by steam and water [1]. This marked the second industrial revolution. Advances in information and communication technologies allowed further improvements to the industry. Computers and microchips led to programmable machines and robots, which allowed the planning of parts and production processes on a computer [2]. Relying heavily on the computer-based improvements of this third revolution, the original concept of industry 4.0 was introduced at the Hannover fair in 2011. It has since become a representation of a production paradigm shift "*from machine dominant manufacturing to digital manufacturing*" [3]. Apart from increasing the efficiency of existing manufacturing lines, Industry 4.0 will significantly alter manufacturing in the following ways:

Flexible production

Mass production has been associated with competitive efficiency and economies of scale and has been the dominant manufacturing paradigm for decades. Manufacturing must become more flexible to handle high variety batches and react quickly to changes in demand or supply.

Rather than static production lines, future manufacturing can quickly be adapted to produce different products to exploit its production capabilities at all times fully. In

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contrast to traditional production lines, cells will be flexible in what they produce in a Matrix production setup.

Mass customisation

As Henry Ford already acknowledged, product variety in traditional manufacturing entails higher costs due to organisational overhead, higher error rates and more complicated logistics. Since then, many processes have been improved, and some product variety can be achieved. This usually includes different colours or minor adjustments due to modular design. Industry 4.0 factories promise individual customisation of the products at a mass production scale [4] without compromising efficiency, speed, or quality. Relying on the aforementioned flexible production and highly digitalised processes, these factories make mass customisation a feasible reality.

> *"Any customer can have a car painted any colour that he wants, so long as it is black." – Henry Ford*

Data-driven factories

Sensors and connected machines enable the collection and exploitation of data. This will allow performance increases and ensure continuous improvements in product quality. Furthermore, maintenance can be scheduled more precisely, and supply chains will become more transparent and traceable, leading to better fulfilment and shorter delivery times. However, this digitalisation has further implications, enabling companies to "*reinvent their products, processes, and value chains, and to enter into new markets"*[5]. This process, called digital transformation [6], describes how a company creates new ways to exploit its available data, potentially changing the company fundamentally. The digital transformation of manufacturing towards Industry 4.0 calls for new strategies and mindsets to drive innovation and fully leverage the opportunities presented by technological change [7], [8].

Using resources efficiently

Every part of the supply chain is expected to become more efficient due to its interconnectivity. Firstly, the products themselves become more efficient, thanks to data-driven optimisation. But also, the scheduling of orders can be optimised to save raw materials and power [9] by reducing overproduction and choosing beneficial timeslots for power-intensive operations. Finally, the working conditions in manufacturing are improved by assigning repetitive and physically demanding tasks to robots or providing supportive tools to the workers [10]. This entails that worker qualification requirements change due to the new tools employed.

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INDUSTRY 4.0 ENABLING TECHNOLOGIES

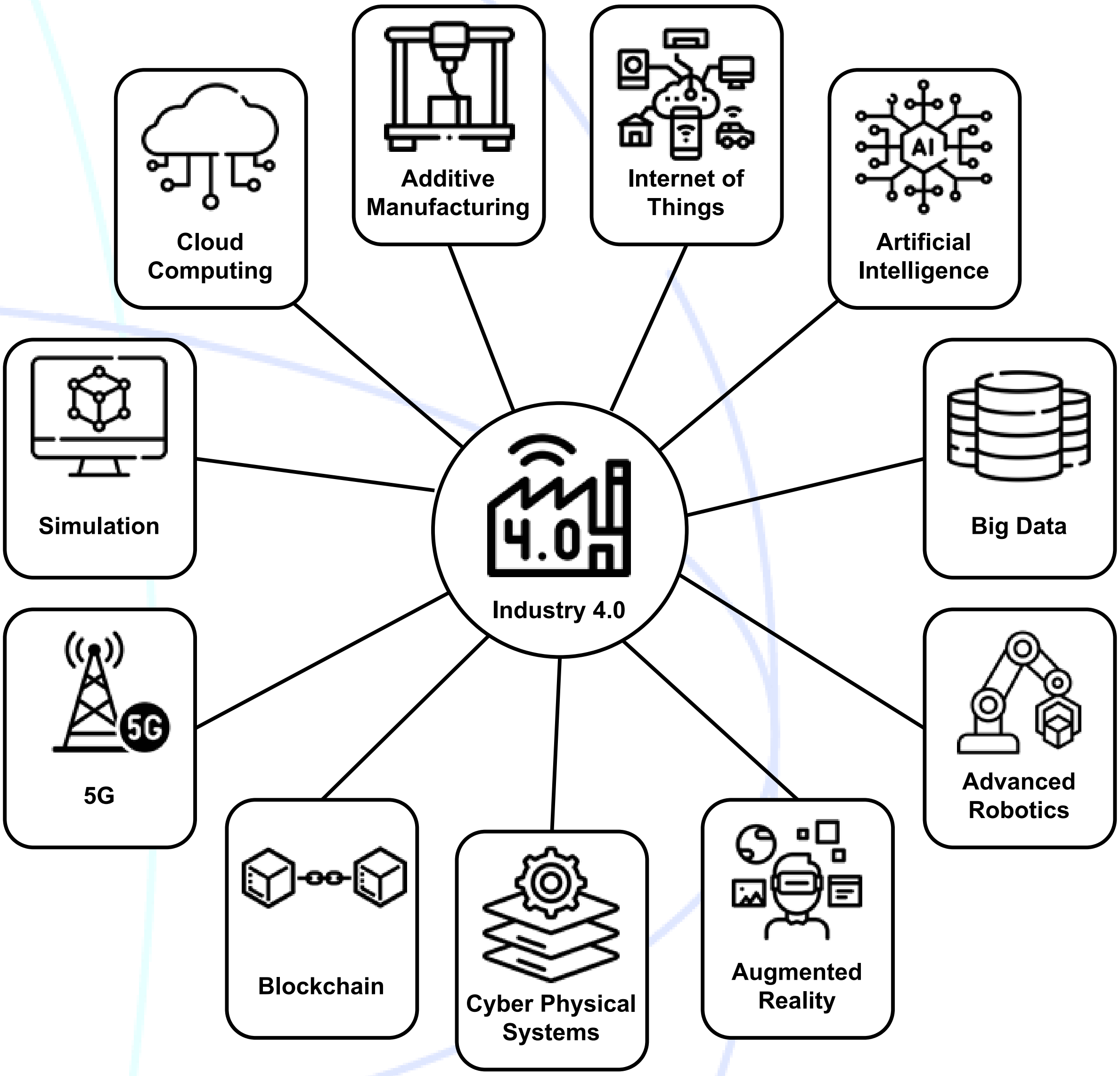

Figure 2: Industry 4.0 enabling technologies, own figure

To realise this vision of the industry of the future, the following technologies are crucial to propel forward the development of industry 4.0. These technologies include Cyber-physical systems, the Internet of things, cloud computing, big data, advanced robotics, augmented reality, simulation, and additive manufacturing [11], [12], as well as blockchain [13], artificial intelligence and 5G [14]. In the following, we will outline the contribution of each of the technologies to the industry 4.0 vision and their current applications.

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CYBERPHYSICAL SYSTEMS

Cyber-physical systems integrate "*the cyber-world of computing and communications with the physical world*" [15]. This means that the system's operation is monitored, coordinated, controlled and integrated by a computing device [15]. In the context of industry 4.0, these cyber-physical production systems are characterised by the ability to obtain data from themselves and connected devices or human input and autonomously react upon it [16]. Cyber-physical systems provide the foundation for most other technologies related to industry 4.0 since they are required to capture data and allow computer-driven monitoring and control of the plant [17].

INTERNET OF THINGS (IOT)

The internet of things describes a collection of vastly different devices that, combined with minimal computing power and wireless networking, can "*generate, exchange and consume data with minimal human intervention*" [18]. Since wireless connectivity and low-power/low-cost sensors have become more accessible, the internet of things has significantly increased in popularity. Smart home devices, wearables and RFID tags are only a few examples of widespread adoption. In the manufacturing industry, internet of things devices can track wares through the supply chain, connect sensors and machines and monitor logistics.

5G

Connected production machines, as well as IoT devices, require appropriate infrastructure to receive and send data. Stability and reliability are crucial when handling sensitive data exchanges such as in power or traffic management. Other applications require extremely low latency when transmitting real-time data to ensure safety and precision when controlling machines. Finally, video feeds and machine learning require immense amounts of data to be transmitted. Current wireless solutions, such as the previous 4G wireless standard, cannot provide the stability, reliability, bandwidth and low latency required. 5G is designed to overcome these limitations and provide a scalable solution for these new demands from industry 4.0 [19].

Table 1: Comparison between wireless standards, adapted from https://www.raconteur.net/technology/5g/4g-vs-5g-mobile-technology/

Wireless standard	**3G**	**4G**	**5G**
Deployment year	2004-05	2006-2010	2020
Bandwidth	2mbps	200mbps	>1gbps
Latency	100-500ms	20-30ms	<10ms
Average speed	144kbps	25mbps	200-400mbps

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BIG DATA

Big Data is an information asset characterised by high volume, velocity and variety and capturing its value requires specific technologies and analytical methods [20]. IoT devices and cyber-physical production equipment can now capture precise data points from machines, such as temperature, pressure or humidity. These data points offer valuable insides into the state of the machines and the quality of the output. Since the effort to capture all this data is continuously decreasing, it is possible to create enormous datasets. Big data is the foundation on which simulations and artificial intelligence are based to improve production processes' quality, reliability, and efficiency [21]. The data gathered is not limited to the production facilities. It can also be captured from the product itself to gather after-sales data, tracking it throughout its entire product life cycle.

SIMULATION

We can no longer only imitate the real world in an independent simulation but can merge the digital with the physical world. Data obtained from cyber-physical systems and IoT devices can be used to augment a simulation. These new concepts demand clarification and have been separated based on the degree of interconnectedness, namely the *Digital model*, *digital shadow* and *digital twin* [22], which will be explained in the next section.

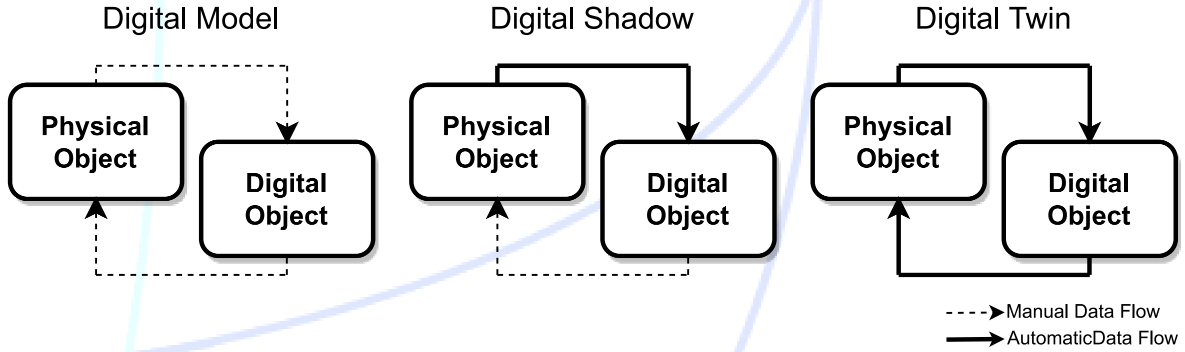

Figure 3: Digital model, Digital shadow and Digital twin, adapted from W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn

Digital model

Digital models are the simplest and oldest relation between the physical and digital worlds. An existing model is recreated in the digital world without automated data exchange. Recreating a production line in a simulation program based on a real-world production line's archival data is an example of such a digital model.

Digital shadow

A digital shadow exploits data obtained by cyber-physical systems to create a one-way connection from the physical to the digital model. Any change in the state of the physical model translates to a change in the digital model. Building on the previous example,

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augmenting the production line simulation with live, real-world data would elevate the digital model to a digital shadow.

Digital twin

A digital twin is created when the cyber and physical space are seamlessly integrated [23], meaning that a real word product or process is directly linked to its virtual representation. Changes in either the digital or physical world will translate to the corresponding counterpart. In our example, this would be equivalent to a simulation in which one could change the state of a real-world machine from within the simulation.

Though digital models existed prior, the increased availability of data allows more sophisticated simulations. Planning future production lines can be done digitally and optimised using sophisticated artificial intelligence trained on archival data. This is not limited to abstracted models but can include high-fidelity simulation with the exact positioning of parts and robots in the production line [24]. Collision detection and precise data for accurate dynamics simulation of robots even allows programming robots in the simulation and then transferring the routine to a robot [25]. Developing new production lines is hence faster, more precise and reduces the risk of unforeseen complications. Furthermore, the physical assets are not at risk when collisions occur during the planning phase of the setup within the simulation.

Digital shadows allow remote supervision of the machines on site. Production status and degradation of the machines can be determined without constant on-site access. Using predictive maintenance, maintenance can be efficiently scheduled, increasing the machines' uptime. At a glance, an entire plant's performance can be evaluated, and data gathered [26] for future reference or to track the impact of changes to the production line. In an iterative loop, this allows continuous improvement of the plant's performance.

Finally, if controlling a machine from the simulation is possible, a manufacturing task can be completed from order to shipment without manual interference. Routines for machines can be preprogrammed, and operators are mostly concerned with maintenance and supervision tasks. A digital twin of the plant and supply chain allows quick reactions to disruptions [27], identifying issues quicker and allowing immediate automatic responses.

CLOUD COMPUTING

Cloud computing describes a technology where instead of executing a computing task on the device itself, the task is jointly solved by a collection of computing devices. As a result, devices that only require heavy computing for a fraction of their operation can use less expensive components and rely on cloud computing whenever their computational capabilities are exceeded. This grants "dumb" devices access to powerful tools at low costs and excellent power

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efficiency [28]. Rather than building up costly infrastructure in-house, companies can rely on cloud computing providers such as Microsoft Azure [29] or Amazon Web Services [30] to perform heavy computing. Without these upfront costs, the barriers to computationally demanding tools such as artificial intelligence are significantly lowered.

ADVANCED ROBOTICS

Robots have been crucial in driving the ever-increasing automatisation in manufacturing. Specialized, highly efficient, yet inflexible machines have characterised the manufacturing sector since the third industrial revolution. Building on top of the advancements made in the field, more flexible robots emerged to aid in processes that were previously unfeasible to automate.

Collaborative Robots (COBOTS)

Traditional industrial robots require heavy fencing since they do not sense their surroundings, which, combined with heavy payloads and high speeds, can seriously endanger human operators. Reacting to the new demand for mass customisation, collaborative robots coined *cobots* [31] emerged as a smaller and safer counterpart to their industrial predecessors. These cobots can operate without fencing and can share a workspace with a human operator. With quick and easy programmability and a smaller footprint, cobots fill the gap for more flexible tasks. The degree to which cobots interact with the human operator can be categorised into four distinct relationships *coexistence*, *synchronised*, *cooperation* and *collaboration* [32].

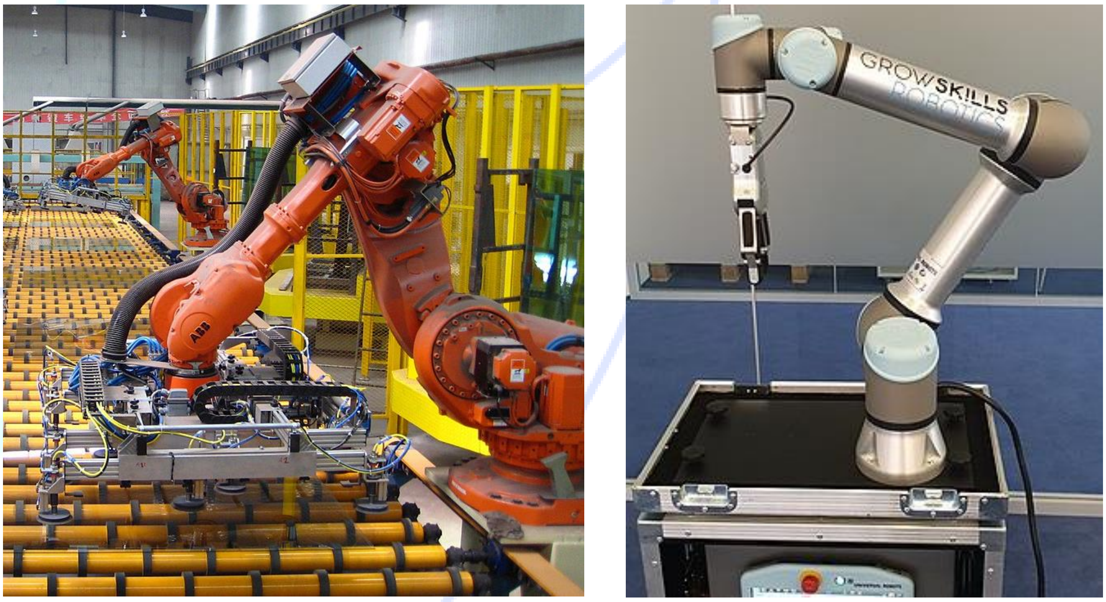

Figure 4: An industrial robot in a fenced environment (picture by ICAPlants, licensed under CC BY-SA 3.0) and a collaborative robot (picture by GrowSkills Robotics, licensed under CC BY-SA 4.0).

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These new ways of interaction redefine which tasks can be done by a robot. Human operators are still necessary for many assembly operations but can now be assisted by a robot to increase performance and well-being by supporting them in strenuous tasks [33]. This combines a human operator's flexibility with a robot's reliability and precision.

Automated guided vehicles (AGV)

Mass customisation means that warehouses must be able to handle small quantity, high variety orders without compromising speed or flexibility [34]. Automated guided vehicles (AGVs) optimise warehousing by aiding or even fully automating the internal deliveries. Using AGVs saves labour costs and reduces the space required for the storage facilities while at the same time ensuring the 24/7 operation of the warehouse [35]. Relieving human operators from the heavy lifting also contributes to a safer work environment.

Figure 5: An automated guided vehicle (picture by ek robotics GmbH, licensed under CC BY-SA 4.0)

ARTIFICIAL INTELLIGENCE

The terms machine learning and artificial intelligence are often used interchangeably. While similar, a distinguishment must be made between the capability of a computer to mimic human abilities (artificial intelligence) and the process of the machine to develop said intelligence (machine learning) [36]. Recent advancements in artificial intelligence do not only stem from an increase in available processing power but also from a significant increase in available data. Many processes can potentially benefit from decision-making done by or supported by artificial intelligence, specifically production monitoring, optimisation, and control in the context of industry 4.0 [37]. We will now have a closer look at the most prevalent application of artificial intelligence in industry 4.0 settings: predictive maintenance.

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Ensuring continuous operation of your production facility is crucial to ensure the feasibility of a production line. Efficiently managing machine breakdowns is hence imperative, and different strategies have been developed to mitigate this impact. Previous to the digitalisation of the factories, two main approaches were most prevalent: *Breakdown Maintenance* and *Preventive Maintenance* [38]. The first option of running a machine until it breaks has the apparent disadvantage that downtimes cannot be avoided since there is no way to predict the occurrence. However, it ensures that no unnecessary repairs and replacements are conducted.

On the other hand, preventive maintenance attempts to mitigate that risk by regularly maintaining the machines without any indication of failure. While this decreases the risk significantly, a slight chance remains that the machine will fail. In addition, this requires potentially unnecessary resources and downtime of the machines in case the machine did not require any repairs.

With the advancement in both tools and the wider availability of data thanks to cyber-physical systems in production, a third option has become more feasible: *predictive maintenance*. When sensor data is combined with expert knowledge, informed decisions based on machine conditions can be made [39]. The benefits of predictive maintenance are threefold; it allows cost reduction, increases operational efficiency and improves product quality [40]. Maintenance costs are reduced because maintenance and replacement of parts exposed to wear are based on the actual condition of the machine. This means that the lifespan of components can be maximised and maintenance frequency minimised. Anticipating failures enables the scheduling of repairs and allows uninterrupted production operation. This additional uptime increases operational efficiency. Last but not least, the product quality benefits from the extra control of the degradation since drift can be anticipated and can not only be prevented but also more easily identified should they occur. This reduced backtracking and the risk of accidental delivery of faulty products.

AUGMENTED REALITY (AR)

In the simulation section, we already established the need to merge the virtual world with the real world. While a digital twin helps run analysis in an office, shopfloor workers cannot benefit from data available in the virtual world without appropriate visual representation. Contrary to the aforementioned simulation, augmented reality is a means of representation, overlaying digital information on top of the physical world to help the worker collaborate seamlessly with machines [41]. While static visualisation by screens and projectors can also serve as a form of augmented reality, mobile devices, especially head-mounted devices, are the most prevalent devices used [42]. Portability and the ability to allow hands-free operation [43] make these especially relevant for manufacturing, as they do not interfere with the operator’s processes. Providing real-time information to workers can benefit their performance in many cases:

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Training

Augmented reality can help train workers and supervise their learning experience. Acquiring skills for delicate tasks which can potentially endanger the operator or product represent a prime opportunity to apply augmented reality. Simulations have already shown great effects in teaching such skills in other fields, such as the medical sector [44], where patient interactions in the learning phase should be minimised. Furthermore, operators can learn faster, memorise the process longer and reduce errors, increasing training performance and quality [45] compared to traditional teaching methods.

Supporting operators

Benefitting from augmented reality is not limited to new operators, as many other processes can also be supplemented by visual guidance. During assembly tasks, the operators can be supported in picking the correct parts [46] and guided through the assembly. Similarly, warehouse operators can be supported by “pick-by-vision” systems informing them of the location of the parts and amounts to pick [47]. All in all, for any task during which “*operators depend on or can profit from (real-time) information, AR can be used to intuitively display this information on site*” [42] and aid them in the process.

Remote support

Last but not least, augmented reality can be used to access expert knowledge remotely. An operator can be paired with a remote expert to aid him in tasks where he lacks proficient skills, such as machine maintenance [48]. Access to such experts can be beneficial in either remote areas or for smaller companies that cannot afford in-house experts covering all required competencies. Product-as-a-service models can significantly benefit from this as well, as suppliers can assist customers in maintaining their product [49] before they have to send an expert, saving money and improving the customer experience due to faster and more precise support.

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ADDITIVE MANUFACTURING

Additive manufacturing, also known as 3D printing, describes the process of recreating a virtual 3D object as a physical part by slicing the object into small layers and joining those by differing bonding methods [50]. This process allows for more complex geometries than traditional manufacturing techniques such as moulding and milling. Air pockets within the part are possible, as the part is created from scratch and later enclosed areas of the part can be accessed during the printing process. Initially used primarily as a prototyping method, advances in material sciences and joining methods have elevated additive manufacturing to an efficient manufacturing method.

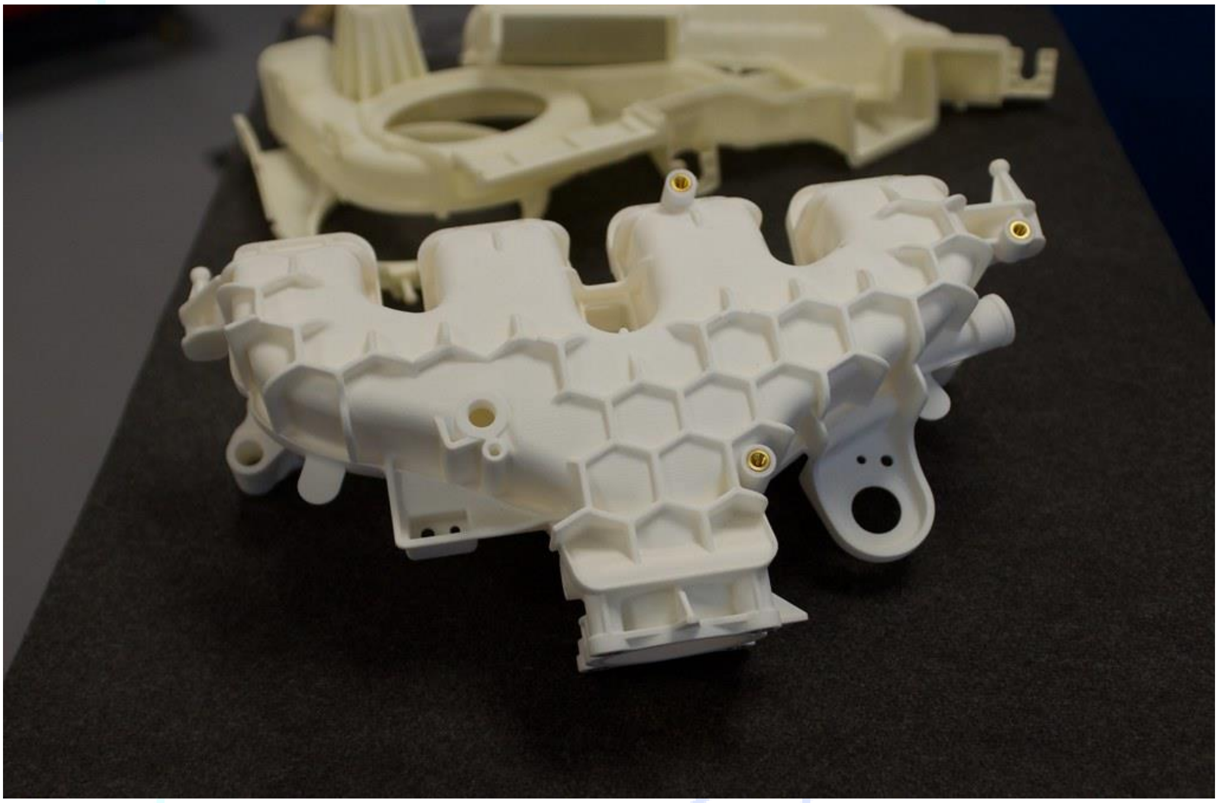

Figure 6: 3D printed car parts (picture by John Biehler, licensed under CC BY-NC-SA 2.0)

Increasing efficiency

Thanks to this different approach to creating parts, additive manufacturing significantly decreases the amount of raw material required. Not only because of more efficient parts due to more liberty in the design process but also since less waste is created in comparison to subtractive manufacturing processes [51]. Furthermore, assemblies that used to require multiple parts can now be merged into a single component, reducing assembly times and increasing part efficiency [52].

Adding flexibility

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Additive manufacturing does not require tooling and can flexibly create varying parts on demand [53], saving costs for equipment such as moulds and allowing quick production of urgently needed parts [54]. Consequently, it is possible and feasible to produce customised products specifically designed for individual needs, such as medical implants [55]. Remote facilities can also benefit from this flexibility since a single 3D printer can produce necessary parts on demand, decreasing dependencies like in the extreme case of the international space station [56].

Prototyping

Due to this flexibility, it is possible to develop prototypes faster and more cost-efficient using additive manufacturing [57]. Rapid on-demand creation of parts speeds up iterative development processes since new models are quickly available. The reduced costs also make experimentation more feasible.

BLOCKCHAIN

Data-driven production requires continuous exchange of data not only between devices within a production site but also other nodes in the supply chain. Suppliers and manufacturers are interdependent and must seamlessly interact to ensure timely deliveries and quick reactions to disruptions. This has created an immense increase in sensitive data that has to be transmitted, which calls for a scalable, robust, transparent, secure, traceable, immutable and low-latency data exchange network [13]. Traditionally, security solutions had high computation and communication costs with a centralised architecture, creating a system with a single point of failure [13]. A possible response to those needs is incorporating blockchain, a decentralised, encrypted, and distributed ledger [58]. Blockchain gained traction with the introduction of Bitcoin, the first cryptocurrency [59]. For better or worse, mainstream attention was mostly given to blockchain’s ability to create such cryptocurrencies, but the general concept can also be applied to other areas. Let us first look at how a blockchain works.

In contrast to centralised systems, a blockchain is stored on many nodes, each holding a copy of the latest chain. Should a node disappear from the network, the operation of all other nodes is unaffected since no node has unique information. In order to better understand its functionality, we now look at a simplified example of a blockchain. The initial block also referred

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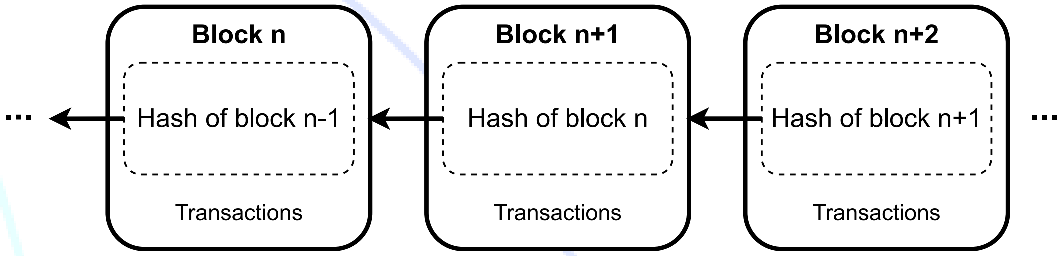

Figure 7: Blockchain function diagram, adapted from K. Christidis and M. Devetsikiotis

to as the "genesis" block, marks the initial state of the network. Now, if two clients of the blockchain wish to interact, they must request this transaction and sign it with the private key of their cryptographic public/private key pair. Doing so allows all clients in the network to validate the identity and validity of the client requesting the transaction. All submitted transactions must adhere to a predetermined set of rules, which are agreed upon at the creation of the chain. Should the transaction request violate any of these rules, the transaction will be discarded. In the case of Bitcoin, this could be, for example, breaking the "double spending" rule, which is attempting to send the same bitcoin multiple times and effectively multiplying it. If the transaction is valid, it will be included in the next block. Each block has a timestamp, as well as a hash which is the result of a cryptographic function based on its content, as well as the hash of the previous block. As a result, each block is directly linked or *chained* to its preceding block and hence the name blockchain. Now that the block has been created, it will be submitted to the network. If the other clients agree with the proposed block, they will add the block to their chain and continue using it in the next cycle. There are different ways of coordinating consensus for this final step, with Bitcoin's "*proof of work*" algorithm being the most famous one, which ensures immense calculating power and, thereby, resources would be necessary to force the network to adopt a block [60]. However, this is hardly the only way to reach consensus and especially considering the resource implications of such a blockchain, energy-efficient alternatives such as "proof of stake" algorithms emerged, where instead of using immense calculating power, clients verify the validity of a block with resources as collateral at stake [60]. Another essential feature of more recent blockchains is the execution of smart contracts, a contract that will execute itself if a previously agreed upon requirement has been met. Instead of manually creating a transaction, a smart contract can be made to handle interactions automatically – a feature that we will explore in more detail later on.

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This should outline the core features of a blockchain; however, the benefits for industry 4.0 remain abstract. Hence, we will look at blockchain applications in the industry 4.0 setting.

Providing security

One of the greatest potentials for blockchain is creating a secure and trusted environment. With the ongoing adoption of IoT devices, this is especially relevant. Managing a centralised system for IoT devices is not only expensive [61] but also risky from a security perspective [62], as sensitive information could be leaked in a data breach. Using a trustless, decentralised network can mitigate those risks [63]. Another benefit of using blockchain is that due to the previously mentioned signing of transactions, the identity and validity of an IoT client can be confirmed effortlessly by all nodes in the network, minimising the risk of malicious requests [64]. Finally, should a client node be unavailable due to, for example, a cyber-attack, the IoT network's operation is not affected, ensuring the continuous operation of all devices and services.

Improving traceability and transparency

Efficiency is not the only benefit of automating and securing the supply chain interactions using blockchain. Some supply chains are more sensitive and require special conditions such as cooling or careful handling. Here the traceability of the blockchain can help make participants accountable for failing to comply with previously agreed-upon transport conditions. In addition, the location of a product can be traced at all times without relying on the current supply chain participant's compliance. This is not limited to accountability regarding physical condition but can also be used to ensure each participant's dedication to sustainability [65].

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DISCUSSION

Each of the described technologies contributes to the vision of transforming the manufacturing industry. Cloud computing, for example, allows Industry 4.0 technologies to be offered as a service and generates business model innovation that opens the field for new entrants and redesigns the industry landscape [66]. Some technologies provide the necessary infrastructure on which other technologies build [67], exemplified by the reliance of augmented reality displays on cloud computing or artificial intelligence on existing big data sets. In the future, new emerging technologies might help overcome the challenges of current solutions in combination with other technologies. This is why the concept of industry 4.0 is ever-evolving, and new technologies have been added throughout the years.

On top of that, some of the most impactful opportunities arise when combining complementary technologies since the result is more likely to lead to further innovation [68]. In the following, we will outline two of those cases. First, we look at how the IoT and Blockchain complement each other and enable smart contracts. Then, we discuss how artificial intelligence and additive manufacturing come together in generative designs:

SMART CONTRACTS (IOT & BLOCKCHAIN)

When paired with IoT-enabled devices, blockchain has the potential to trace and manage complex supply chains automatically [61]. Two companies can agree on an interaction and formulate a smart contract based on this agreement. Take, for example, a simple exchange between a shipping company and a warehouse. Instead of manually checking whether a container arrived at the warehouse, the container can be equipped with an RFID tag, and the delivery will be validated automatically upon arrival. This will trigger a smart contract, which will transfer the container from the shipping company's inventory to the warehouse's inventory while simultaneously validating the successful delivery for all parties involved. Based on this, other actions can be taken, such as automatic payment of the delivery fee. On the other hand, not fulfilling a smart contract within a timeframe could trigger an automated investigation and potential compensation for the loss of the container. All of this decreases the amount of organisational effort required and minimises human error.

GENERATIVE DESIGN (ARTIFICIAL INTELLIGENCE & ADDITIVE MANUFACTURING)

Reaping the benefits of artificial intelligence is not limited to processes but impacts the development of products as well. Rather than designing parts by hand, the design process can be supported by generative design algorithms. Given constraints such as the forces which must be supported, material properties, fixed points where other parts are connected and maximum dimensions, parts can be created autonomously by software. Not only does this significantly

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speed up development time, but it can also optimise the weight and dimensions of the part. In addition, this reduces the material used and grants the development team more flexibility as parts can be redesigned quickly when changes to the requirements are necessary due to, for example, interdependencies with other components. The development of this technology goes hand in hand with additive manufacturing, as these parts tend to be more complex and are impossible or unfeasible to produce with traditional manufacturing processes. This allows further optimisation of components, decreasing weight without sacrificing stability. Especially in the automotive industry, as well as the aviation industry, further weight reductions can be made to increase efficiency [69].

Figure 8: Generative design model of a car chassis (picture by Steve Jurvetson, licensed under CC BY 2.0)

UNDERSTANDING THE COMPLEXITY

The above examples of the interaction of different technologies within the Industry 4.0 help us understand the complexity that companies face. Merging the digital world with physical processes has become more and more realistic and resulted in the emergence of many new technologies which can reshape manufacturing. However, many issues remain to be solved. Rethinking how to handle manufacturing will not be easy for highly specialised companies, and they may face fierce resistance from current employees who fear losing their position. Moreover, many technologies are heavily intertwined and cannot unleash their full potential without proper implementation and standardisation of the other technologies [68]. Companies can hence no

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longer feasibly secure all required competencies by in-house experts but need to open up their innovation process.

Additionally, the relations between other down or upstream companies become increasingly complex and interdependent [70]. Hence it is no longer suitable to employ a supply-chain view but rather an ecosystem approach [71]. Within such an innovation ecosystem [72], loosely coupled and interdependent actors contribute to a joint value proposition. For such complex ecosystemic interaction, the included technologies need to have modular characteristics [73]. Technology interfaces also need to be standardised to leverage modularity and avoid inertia of legacy systems [74]. Steering such an ecosystem will require orchestration, not only by governmental bodies but also from actors within, to secure "knowledge mobility", “innovation appropriability," and “network stability” of the ecosystem [75].

Furthermore, data without standardisation is of little value outside of the company itself and implementing standards will prove challenging given the enormous range of data types and applications [76]. Regulators must establish clear legislation for data rights, especially after-sales data gathered from the product. Both for data and technologies, ecosystemic IP rights are a conundrum due to the lack of a regulatory framework to manage complex and indirect interactions [77].

THE WAY FORWARD

Adapting to these new circumstances will be challenging for established companies and might reshape the competitive environment. Yet it is crucial for the industry to accept the dissolving borders in the supply chain and jointly create more efficient manufacturing processes and better products. Otherwise, entire industries might face extinction by being unable to compete with others who have embraced the new way of manufacturing.

The new technology landscape described here is not only enabling more efficient and flexible manufacturing. In addition, Industry 4.0 enables the birth of entirely new technological innovations [78]. Artificial intelligence can be an originator or facilitator of innovation [79] and therefore becomes a structural element that guides firm strategy [80]. Manufacturing firms are therefore well advised to develop AI capabilities and engage in business model innovation, e.g., towards digital servitisation [81]. As AI becomes commoditised, the dominant business model for AI provision is increasingly cloud-based, allowing smaller companies to innovate based on AI [66].

A similar reasoning could be applied to the entire set of Industry 4.0 enabling technologies: As technologies grow and a dominant design is established, the technology becomes a commodity. The industry’s challenge is no longer to develop the technology itself but to generate

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complementary innovations that use Industry 4.0 technologies, i.e., to enable breakthrough innovations in terms of technologies, services, or business models.

SUMMARY

The physical world is increasingly connectable with the digital world. Industry 4.0 describes a possible way to revolutionise manufacturing by exploiting these new possibilities. Various technologies, which facilitate data collection, transmission and evaluation and allow autonomous reactions upon it, will enable this revolution. Some technologies are interdependent and can only fully unleash their potential in combination with other technologies. These beneficial interactions will also shape the dynamic evolution of the industry 4.0 concept in the future when new technologies or synergies emerge. The increasing complexity of the interactions requires a change in perspective, abandoning the supply chain view for a less formal interconnected system of actors in the ecosystem perspective.

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