32nd European Modeling & Simulation Symposium
17th International Multidisciplinary Modeling & Simulation Multiconference

2724-0029 © 2020 The Authors.
doi: 10.46354/i3m.2020.emss.060

Machine Tool 4.0 in the Era of Digital Manufacturing

Dimitris Mourtzis[1],*

[1]Laboratory for Manufacturing Systems and Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, Rio Patras, 26504, Greece

*Corresponding author. Email address: mourtzis@lms.mech.upatras.gr

Abstract

Under the Industry 4.0 framework, a plethora of digital technologies and techniques has been introduced in the Manufacturing domain. Machine tools must become more intelligent, in order to create a network of fully connected machines. By extension, this will lead to the creation of the Industrial Internet of Things (IIoT). Although these technologies provide for increased functionality of the manufacturing equipment, there are certain issues/implications, refraining engineers from integrating such technologies in the production. Therefore, in this paper, the results of a systematic literature review are presented and discussed, including the horizontal and vertical integration of such digital technologies. The contribution of this paper extends to the recognition of the opportunities emerging as well as the identified implications from a practical implementation point of view.

Keywords: Machine Tool 4.0; Industry 4.0; Human Machine Interface

1. Introduction

The shift towards manufacturing digitalization has earned a lot of attention over the last decade. The main challenges of modern production systems are the unpredictable demand volatility, higher quality requirements, personalized and customized commodities, and the advent of smart supply chains (Mourtzis and Doukas, 2014). From the first industrial revolution in the 19th century through mass production and automated manufacturing processes in the 20th century to the fourth industrial revolution, Industry 4.0, which is part of the High-Tech Strategy 2020 Action Plan adopted by the German government, tremendous amounts of innovative changes have taken place in the industry (Guerreiro et al. 2018; Kagermann 2013). The digitalization of manufacturing introduces an ecosystem of different technologies in the fields of sensing, connectivity, data modeling and decision-making (Mourtzis et al., 2018). Furthermore, communication networks and frameworks such as Wireless Sensor Networks (WSN), Industrial Networks (ModBus, ProfiBus), and Web services are essential facilitators of the continuous flow of knowledge between different systems [Mourtzis et al., 2018]. However, more than 90% of industrial resources are not incorporated into the industrial communication network (CISCO, 2015). The production efficiency and effectiveness of machine tools significantly affect the performance of manufacturing systems. The integration of RAMI 4.0 and Industry 4.0 bridges the gap between production-level requirements and Industry 4.0 technologies, leading to cyber-physical production systems (CPPS) (Mourtzis et al., 2019). There is an urgent need to advance current Computer Numeric Control (CNC) machine tools to a higher level of communication, usability, intelligence, and autonomy in response to CPPS (Wang et al., 2015; Mourtzis and Vlachou, 2018; Monostori L., 2014). Additionally, the integration of RAMI 4.0 and Industry 4.0 bridges the gap between production-level requirements and Industry 4.0 technologies, leading to CPPS. A typical CPPS contains intelligent machines, warehousing systems, and other production facilities and can contribute to more flexible and more efficient production. Therefore, machine tools are vital components of industrial manufacturing. Following the challenges to advance to Machine tool 4.0 under the framework of Industry 4.0 requirements, this paper presents the challenges and latest advances of machine tool evolution in recent literature. Some challenges identified so far by the author, are listed in Table 1. The remainder of the paper is structured as follows. In Section 2, the research methodology is presented. Then in Section 3, the evolution of Machine Tools is discussed. In Section 4, the evolution of human operators is presented.

In Section 5, the Human Machine Interfaces are discussed. In Section 6, the latest trends regarding Automation in modern manufacturing cells are presented. In Section 7, a short discussion on non-conventional manufacturing processes is performed. Finally, in Section 8, conclusions are drawn and directives for future research work are pointed.

2. Research Methodology

In the following paragraphs the research methodology for the selection and analysis of the most relevant publications is discussed, regarding the horizontal and vertical integration of the Machine Tool 4.0, as well as the technologies and techniques that will enable this transformation. The review is mainly based on the examination of peer-reviewed publications which focus on the discussion of the new generation of machine tools, the Machine Tool 4.0. Concretely, the research methodology is based on the creation of structured research queries, implemented on well-known databases such as Google Scholar, ResearchGate, ScienceDirect, Scopus, and Web of Science. An indicative example of a structured query is formed as follows. The **Title**, or the **Abstract**, or the **Keywords**, must contain either of the following terms, “Industry 4.0”, “Machine Tool 4.0”, “Smart Manufacturing”, “Cyber Physical Systems”. Moreover, in order to exclude irrelevant publications, the publication year has been limited to 2011 and onwards, as 2011 is considered the year which the term Industry 4.0 was established from Academia. The search returned 193,173 documents in Scopus. Similarly, the results returned from Science Direct were 187,379 and from Web of Science 201,623, respectively.

“TITLE-ABS-KEY (industry 4.0) OR (machine AND tool 4.0) OR (smart AND manufacturing) OR (cyber AND physical AND system) AND (LIMIT-TO (PUBYEAR ,2021) OR LIMIT-TO (PUBYEAR ,2020) OR LIMIT-TO (PUBYEAR ,2019) OR LIMIT-TO (PUBYEAR ,2018) OR LIMIT-TO (PUBYEAR ,2017) OR LIMIT-TO (PUBYEAR ,2016) OR LIMIT-TO (PUBYEAR ,2015) OR LIMIT-TO (PUBYEAR ,2014) OR LIMIT-TO (PUBYEAR ,2013) OR LIMIT-TO (PUBYEAR ,2012) OR LIMIT-TO (PUBYEAR ,2011))”

The second step in the screening process of the results returned from the search process involved the selection of the most appropriate publications based on their Abstract section. Consequently, the results have been further reduced. Then, the third step in the review process involved the reading of the full text of the selected publications. Finally, the reviewed articles were limited to approximately 2,000.

However, in an attempt to form a more complete review of the current situation including the current State of the Market, besides the scientific publications, the research of the author expands to technical reports, white papers and reports from top practitioners and leading companies in the field of Industry 4.0, and IoT.

3. Literature Review

3.1. Evolution of Industry, Machine Tool, and Operator

The evolution of industrialization has greatly influenced the evolutionary history of machine tools. As illustrated in Figure 1, industrialization can be split into four industrial revolutions, i.e. Industry 1.0 (mechanization, end of the 18th century), Industry 2.0 (mass manufacturing, beginning of the 20th century), Industry 3.0 (automation and IT, beginning of the 1970s) and Industry 4.0 (digitalization based on cyber-physical structures, present time)(Mourtzis and Doukas, 2014; Kagermann et al., 2013). Similarly, the evolution of machine tools can be summarized in four stages namely Machine Tool 1.0 (mechanically driven but manually operated, late 18th century), Machine Tool 2.0 (electronically driven and numerically controlled, mid-20th century), Machine Tool 3.0 (computer numerically controlled, late 20th century) and Machine Tool 4.0 (Cyber-Physical Machine Tool 4.0). The term "Machine Tool 4.0" stands for a modern technical evolution of machine tools driven by recent advances in Cyber-Physical Systems (CPS), the Internet of Things (IoT) and Cloud-based applications (Xu, 2017; Liu et al., 2018). Further to that, the Operator 4.0 (O4.0) has come up as a new term in the Industry 4.0 framework, following the evolution of generators in parallel with the first three industrial revolutions (Romero et al., 2015). As per the definition by Romero et al. (2016) the O4.0 is defined as “a smart and professional operator who performs not only robot cooperative work but also machine-assisted work if and when necessary”. Moreover, as stated by Gazzaneo et al. (2020) the O4.0 is considered as a hybrid agent created as a symbiotic relationship between the person and the machine, concentrating on the treatment of automation as a further development of the human’s physical, sensory and cognitive capacities.

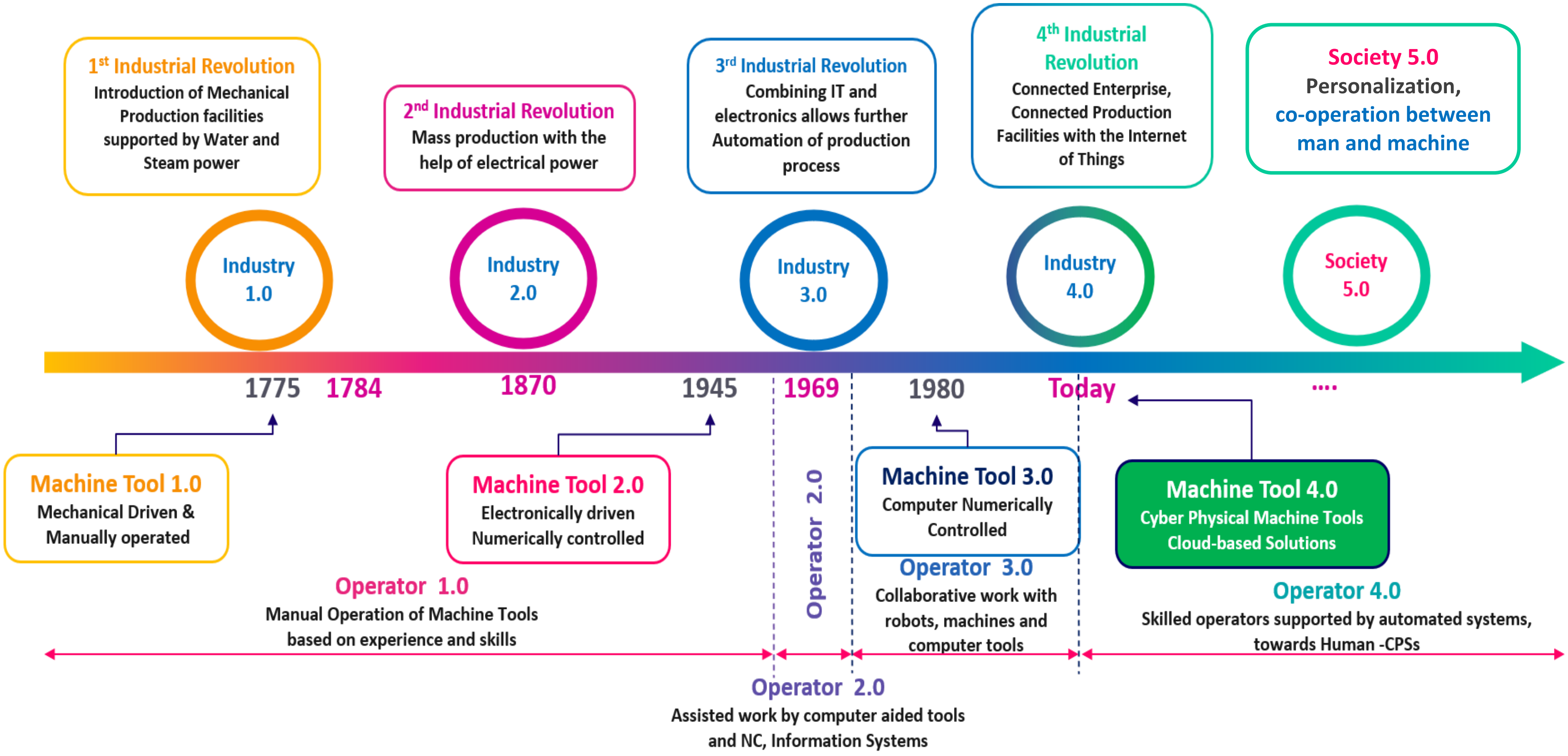


Figure 1 Evolution of Industry, Machine and Operator (Adapted from Romero et al., 2016, Benotsmane et al., 2019, Liu C. and Xu X., 2017)

Table 1 Gap Identification for Machine Tool 4.0 integration

Identified Literature Gaps	Motivation	Proposed Approach	Proposed Solution/Framework	Reference
The requirement for the effective modelling of manufacturing systems with semantic encapsulation Needs for real-time synchronization of the Physical system and its Digital Twin	The motivation for a general machine model for Machines 4.0 through OPC-UA	A multiscale modelling practice towards the concept of Machine Shop 4.0, enabled by OPC-UA. The proposed approach includes three steps, namely the data modelling, the model realization, and the data acquisition.	The Machine 4.0 "Milling Machine" entity is a specialization of the class "Resource". Therefore, it inherits the main parameters of the "Resource" class and extends them according to the modelling needs The subcomponents are specifications of the class "Component" Monitoring devices measure the actual operating time of each component, to determine the remaining operating time until maintenance The process parameters can be obtained directly through the machine controller using the MTConnect interface	Mourtzis et al., 2018
The need to estimate the impact of a monitoring system, developed for machine-tools in the industrial data	Monitoring system via Wireless Sensor Networks (WSN)	Development of a monitoring tool organized in a wireless sensor network (WSN).	A framework that consists of: Sensors on machine-tools organized in a WSN Camera for supervision and safety Mobile devices for the operators A central Cloud server Integration with industrial equipment through OPC-UA OPC-UA is a key enabling technology for the realization of Industry 4.0 It is a safe, reliable, manufacturing and platform independent standard. The physical objects are represented through semantic modelling	Mourtzis et al., 2019
The difficulty to track and monitor assembly processes in Structural Steel Fabrication, and the calculation of important Performance Indicators Complications related to the estimation of the cost for a job during the offering of a quotation	Machine Monitoring through the IoT paradigm Real-time information on the utilization of resources Performance indicator calculation	A method for monitoring the production in structural steel manufacturing considering the Internet of Things and analyzing the data aiming to calculate product assembly complexity and reuse data to retrieve similar past orders.	The proposition of an Internet of Things-based monitoring framework Monitoring of manual operations by utilizing the complexity of an assembly Case-Based Reasoning for the retrieval of past orders and knowledge reuse Through wireless communications, the physical resources connect to the cyber world forming a Cyber-Physical System (CPS)	Mourtzis, Milas et al., 2018
Devices used in the shopfloor are resource constraint and designed with minimum or no security mechanisms. However, they process and propagate sensitive data on a daily base. Thus, they are ideal targets for adversaries and third parties.	The aim of this work is to highlight the importance and need of cybersecurity at every layer and node before providing a service to users.	Identification of the vulnerabilities of main protocols, used in the shop floor, and design of a robust network implemented on a real case scenario, with solutions to countermeasure these vulnerabilities and provide a secure environment.	A data acquisition device (DAQ) was designed for upgrading production machinery into a Thing that can be connected to a WSN The IoT monitoring device supports the integration of equipment and IT tools. In the designed network, a Raspberry Pi 2 micro-computer acts as an OPC – UA server To prevent any DDoS attacks a Virtual Private Network (VPN) is set to masquerade the IP address of the network with an IP from an external server. Thus, in DDoS attacks only the external server will be affected	Mourtzis, Angelopoulos and Zogopoulos et al., 2019

Machine tool operators constitute integral parts of the industrial ecosystem. The development of machine tools has led to the evolution of operators since a symbiotic relationship between them has always existed. From the late 1700s to the late 1950s, operators manually controlled machine tools, based on their skills and experiences. This formed the Operator 1.0 generation as defined in (Romero et al., 2016). The Operator 2.0 generation that followed up to the late 1960s, performed assisted work since the development and implementation of numerical control (NC) facilitated industrial operations. The advancement of technology and robotics shaped the next generation of operators 3.0. Human operators and robots co-existed and collaborated in industrial environments, combining robot abilities and precision with human intelligence (Michalos et al., 2014). The following Operator 4.0 generation in the advent of the Fourth Industrial Revolution, consists of smart and skilled operators, who are supported by automated systems (Romero et al., 2016). New technical enablers will expedite the fourth generation of operators with every day physically demanding tasks such as exoskeleton devices (Bogue, 2018, De Looze et al.,2016), wearables devices such as smartwatches, that enable interaction and communication between operators and robot resources (Gkournelos, et al.2018) and the use of Augmented and Virtual Reality which are ways to display a variety of data in an easily apprehensible way (Mourtzis et al.,2020).

3.2. From Traditional Manufacturing to Industry 4.0

Industry 4.0 or Industrial Internet of Things (IIoT) refers to the industrial transformation based on the utilization of emerging digital technologies for enabling data collection and analysis through devices and business systems. Thus, quicker, more flexible, and more effective manufacturing processes can be adopted for the production of high-quality, low-cost, highly customized goods (SAP, 2016). The growing demands of the market for better quality and personalized goods determine the acceptance of new technologies. The philosophy of Industry 4.0 encourages the digitalization of traditional production. As such, the production system is turned into an ecosystem of entities that interact in a ubiquitous manner (Mourtzis, 2020). Nevertheless, more than 90% of the manufacturing resources are not integrated in the industrial communication network (PWC, 2018).

Moving on to the current pandemic crisis due to SARS-CoV-2, the reaction of the companies to COVID-19 challenges should accelerate the digital transformation already underway in many manufacturing environments. Therefore, real-time data collection and advanced analytics tools may provide a more comprehensive, reliable, and up-to-date image of plant operations for teams operating remotely. As stated by Furtado et al. (2020), new digital approaches can accelerate the capability-building process and allow employees to develop new skills remotely, as depicted in Figure 2.

Real-time Data Collection
Digital Capability Building
Augmented Reality Capability Building for Operators
Remote Meetings
In-line or Remote Quality Testing
Track-and-Trace Functionality
Advanced Solutions to Monitor Supply Chain Vulnerability
Autonomous Planning to Identify Demand Changes

Figure 2 Digital capabilities to manage a Factory 4.0 during the Covid-19 era (Adapted from Furtado et al., 2020)

3.3. Technology trends that form the building blocks of Industry 4.0

The rise of new digital industrial technologies, known as Industry 4.0, is a transformation that makes possible the collection and data analysis across machines, allowing the production of higher quality at reduced costs in faster, more flexible, and more efficient processes. This manufacturing revolution will boost productivity, shift economics, promote industrial growth, and alter the workforce profile, ultimately altering the competitiveness of businesses and regions. Advanced digital technologies are already being used in manufacturing, however with Industry 4.0, the production is being transformed. Moreover, it will lead to higher efficiencies and alter traditional supplier, manufacturer, and customer production relationships, as well as human and machine relationships. The building blocks of Industry 4.0 can be summarized into the nine technology trends presented in Figure 3 (BCG Analysis, 2020).

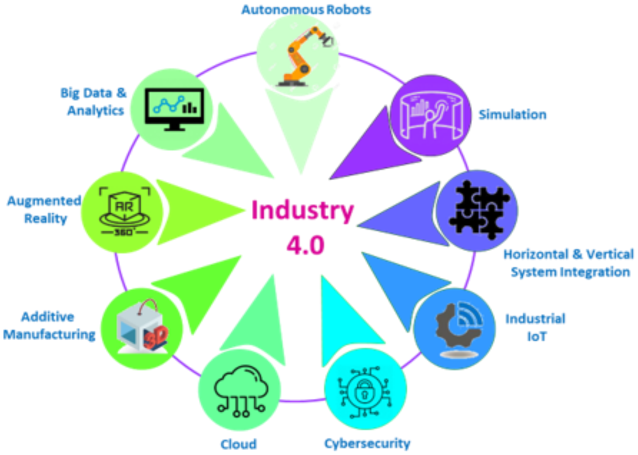


Figure 3 The nine pillar technologies that will shape the modern Industrial Production (Adapted from BCG Analysis, 2020)

3.4. State-of-Practice

The paper by Mourtzis et al. (2019) aims to identify and map the potentially vulnerable endpoints in an industrial case study (i.e. laser machine), as depicted in Figure 6, and propose a way of securing a Wireless Sensor Network (WSN). As such, the IoT monitoring device is designed to support the integration of equipment and IT tools. The most potential standard for this purpose, with more than 48% company members in Europe, is the OPC Unified Architecture. Thus, in the designed network, the Raspberry Pi 2 acts as an OPC – UA server. Next, the power supply board for the auxiliary board is a DC – DC voltage converter, in order to avoid power depletion attacks aiming to drain its battery life. Moreover, the entire DAQ device is enclosed in a plastic transparent box to prevent any unauthorized physical intrusions. Last, the transmitted data from the microcontroller to the DAQ device to the Cloud Database are encrypted using the Advanced Encryption Standard (AES) algorithm.

It uses cryptographic keys of 128-bits to encrypt/decrypt data and requires a lot of time and effort to brute force the key using a sniffing attack. Furthermore, to prevent any DDoS attacks a Virtual Private Network (VPN) is set for masquerading the IP address of the network with an IP from an external server. Thus, in DDoS attacks only the external server will be affected. The designed IIoT network with the implemented security mechanisms is presented in Figure 4.

The monitoring service offers integration capabilities with business applications in order to support decision making. Moreover, the automation levels of a company will be increased by reducing the manual work along the production line. The information obtained from the production line is analyzed, aiming to calculate the production period of a new project more accurately, to track the progress of a project, and to monitor the usage of resources. In the paper by Mourtzis – Liaromatis et al. (2018), a device for monitoring the key operating characteristics of manufacturing equipment is proposed to achieve these objectives. The monitoring sensors have minimal capabilities in the current situation and work offline. Therefore, to evaluate this information and generate knowledge about the operation of production, a lot of manual work is required. The multi-layer architecture is presented in Figure 5.

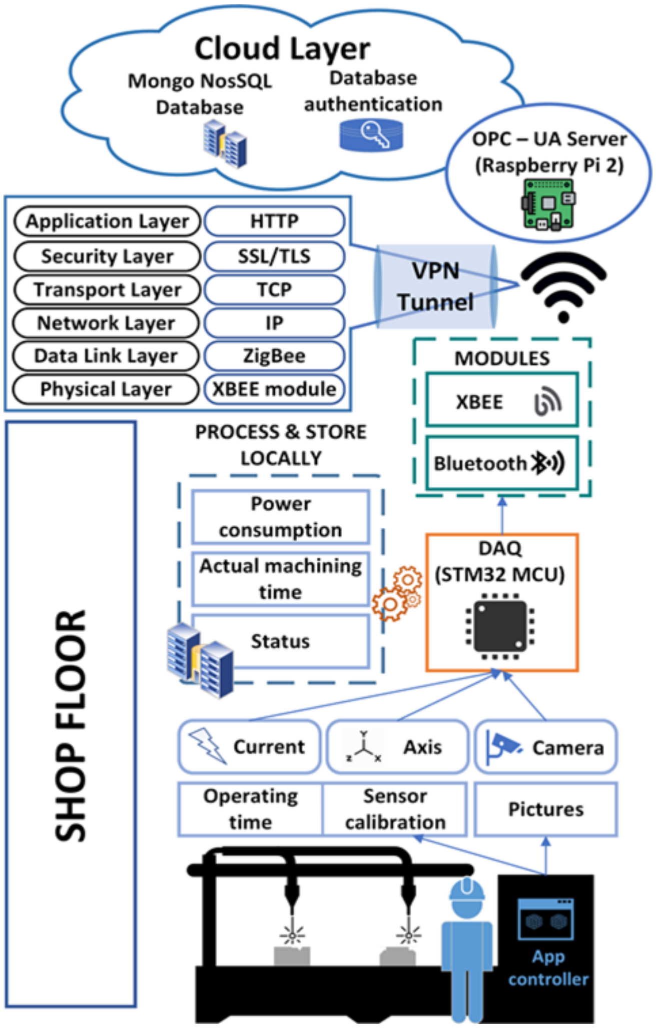


Figure 4 Designed IIoT network with security mechanisms implemented

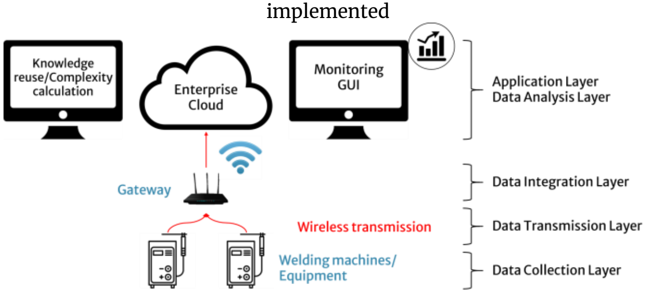


Figure 5 Digitalized Way of Operation: IoT-based monitoring

3.5. State of the Market

Industry 4.0 is causing precipitous changes in the industry and how businesses face their challenges. Highly advanced, intelligent machine tools will boost productivity and make business more competitive in the era of the Fourth Industrial revolution. DMG MORI presented an innovative project, known as Machine Tool 4.0., developed in collaboration with its technology partners, a milling machine used in volume production of rolling bearings, equipped with more than 60 sensors that transmitted digitized information on components from the sensors to the Cloud for the purposes of data collection, storage and analysis (DMG MORI, 2020). In the research work of (Xu X., 2017) the Machine Tool 4.0 concept is described where machine tools become Cyber-Physical Production Systems (CPPS), well connected, smarter, safer, more reliable, and more adaptive. A three-layer Cyber Physical Machine Tool as a promising development trend of machine tools in the era of Machine Tool 4.0 is proposed in (Liu C. and Xu X., 2017) in order to illustrate both the vertical integration of various smart systems at different hierarchical levels and the horizontal integration of field-level manufacturing facilities and resources. In addition, a machine tool architecture conforming to Industry 4.0 is derived in (Jeon B. et al., 2020) from stakeholder requirements, translated into design considerations, largely in terms of Industry 4.0 components, machine tool self-intelligence and contribution to autonomous operation. Chen J et al. in reference (Chen J. et al., 2015) propose a method to build a CPS model of a CNC machine tool work process based on instruction domain electronic data analysis. This work-process CPS model is established on the basis of the accurate, real-time mapping of the manufacturing tasks, resources, and status of a CNC machine tool.

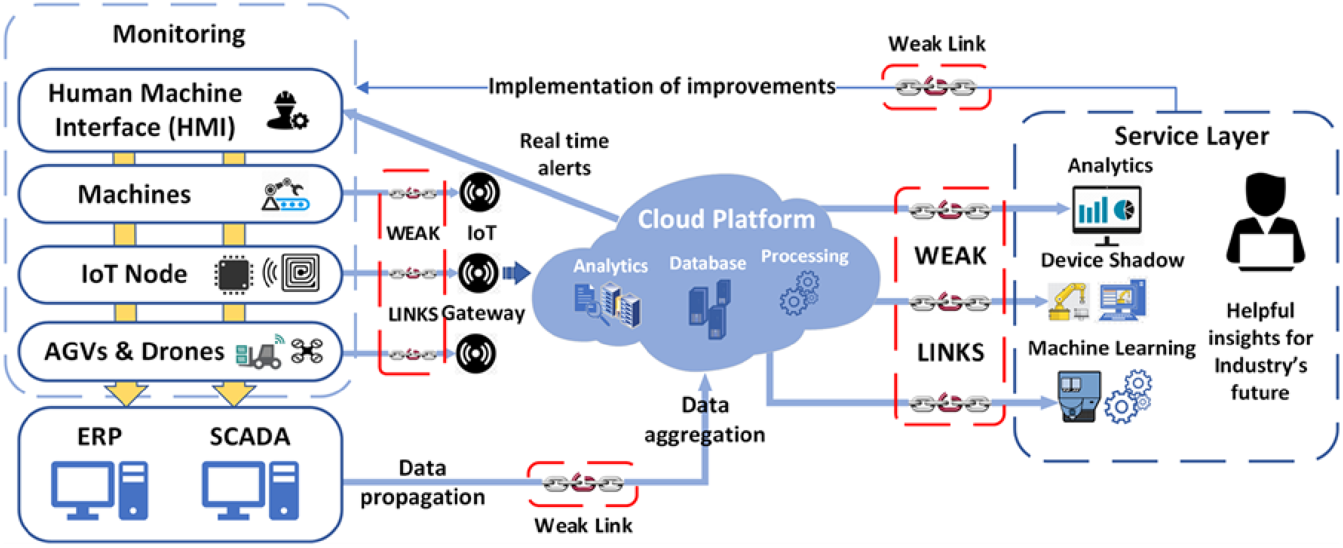


Figure 6 A typical IoT network and its vulnerabilities

The paper by Mourtzis et al. (2018) presents the modeling of machine tools that belong to a Machine Shop 4.0. In particular, the machine tool is divided in its subcomponents, and information is collected in a multiscale approach. The digitalization of the machine shop consists of three measures. The first step is the design using the Unified Modelling Language (UML) of the model. The key entities of the system and their attributes are defined in this stage. The Machine Shop 4.0 is built on the basis of the main performance indicators and support on maintenance activities. The "Machine Shop", the "Resource", the "Part", and the "Process" are therefore the entities of the model. Moreover, the communication standard implemented in this case study is the OPC-UA. Next, the data capturing from the Machine Shop 4.0 is done with a developed data acquisition device. The overview of the proposed method is depicted in Figure 7.

4. Cyber-Physical Machine Tool (CPMT)

As it is stated by Zhu and Xu (2020), full vertical and horizontal integrations are made possible with Machine Tool 4.0. Machine Tools are no longer considered as a piece of production equipment, but they can be service and solution providers (Xu, 2017). Cyber-Physical Machine Tools (CPMT) is one of the potential solutions to Machine Tool 4.0, reflecting a new generation of machine tools that are smarter, better connected, broadly available, more adaptive, and more autonomous (Liu and Xu, 2017). As per the State of the Market status, companies such as SETP Tools (Digital Thread for Manufacturing, 2020) and DMG (Product overview of DMG MORI, 2020) have also produced a digital CNC machine solution to manage the design, development and inspection of a product linked to the Digital Twin. Both industry and academia are trying to incorporate Cyber Physical Systems (CPS) technology in machine tools. The CPMT definition was proposed in 2017 as a promising development trend for machine tools in the Industry 4.0 era and is characterized as a CPS-based machine tool with advanced intelligence, autonomy, and connectivity. As presented in Figure 8, the CPMT generic architecture consists of four components which are: a) Physical Machine Tool and Processes, b) Digital Twin Machine Tool, c) Cloud-based Services and d) Smart Human-Machine Interfaces (HMIs).

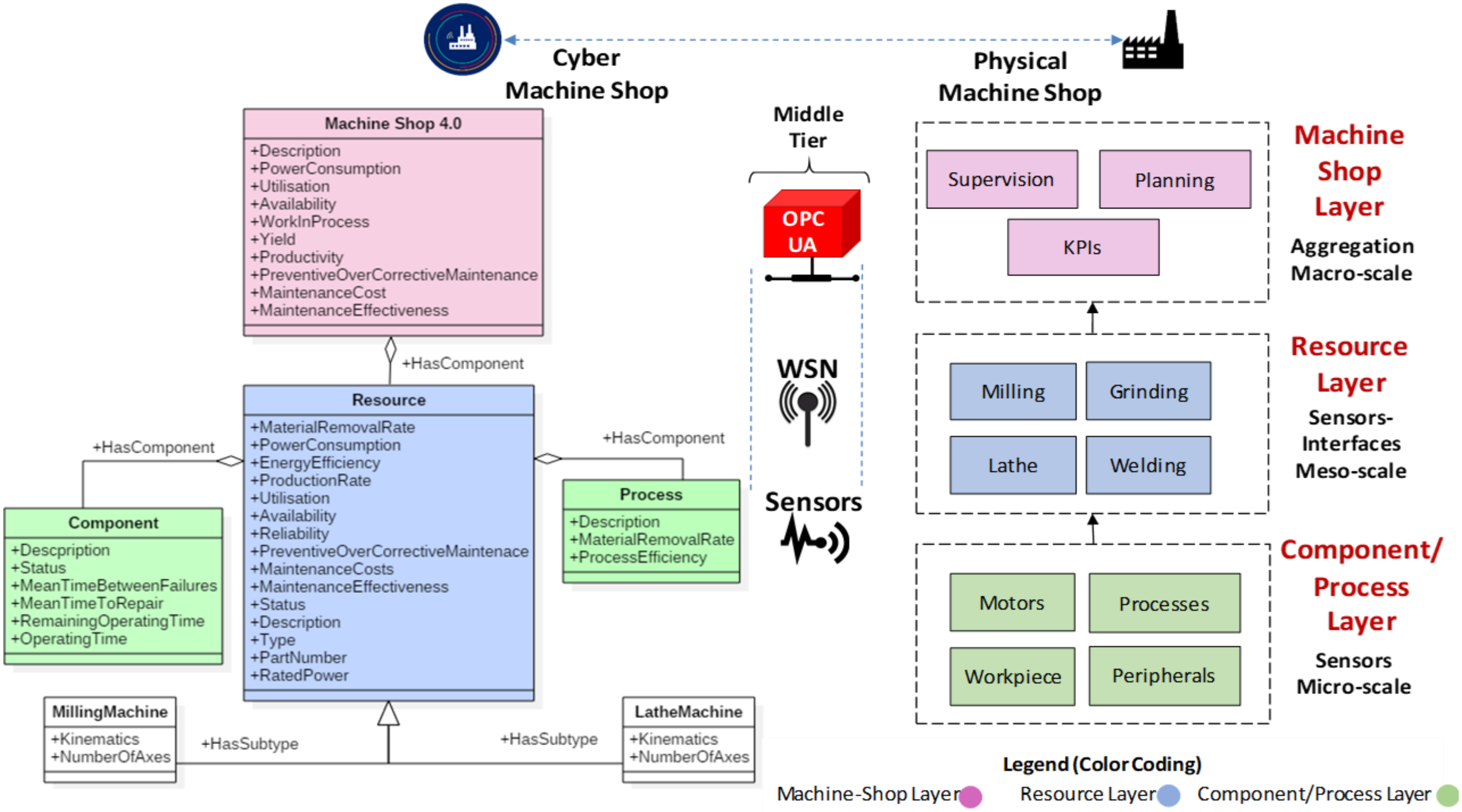


Figure 5 The overview of the Machine Shop 4.0

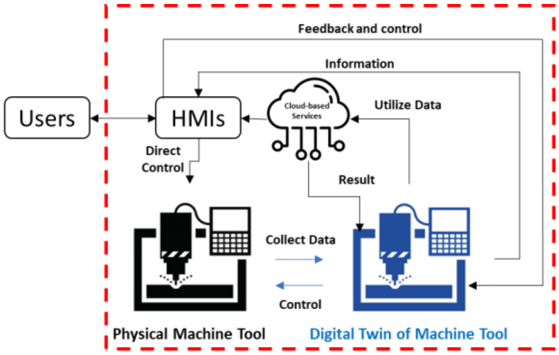


Figure 6 The architecture of CPMT (Adapted from Zhu and Xu (2020))

The three main components of the Digital Twin Shopfloor (DTS) based on Tao and Zhang (2017) are the Physical Devices, the Networks, and the Machine Tool Cyber Twin (MTCT).

Physical Devices: This component consists of the data acquisition devices (DAQ) and the machining devices.

- DAQ: sensors, Radio Frequency Identification tags and readers (RFID), acoustic emission sensors, power meters, dynamometers and so on.
- Machining devices: each component of the CNC machine tool, cutting tools and the workpieces.

Networks: Among other challenges, the most important issue regarding machine tools, is the selection and implementation of suitable communication protocols (Schmied et al., 2020). Based on the research work presented by (Lu et al., 2020), Smart Manufacturing will be based on the integration of the OPC UA architecture for the Machine to Machine (M2M) real-time communication. The authors in (Marcon et al., 2017) have concluded that OPC UA is the most viable solution. Machine tools are constantly improved as part of the upscaling of the Manufacturing domain. However, under the realm of Industry 4.0, machine tools must become more intelligent/smart, adapt based on the needs of the manufacturing system, and most importantly, must achieve a higher level of connectivity. In an attempt to address these issues (Liu et al., 2019) have proposed a platform based on the combination of OPC UA and MTConnect architectures. Although machine connectivity has been achieved to some extent, the complexity and costs added when dealing with multiple solutions increase. Therefore, new technologies must be introduced in order to conclude to a more universal/unified solution. A new trend in the field of communication architectures is the utilization of Time-Sensitive Networking (TSN) in conjunction with the OPC Unified Architecture (Bruckner et al., 2019). Further to that, the integration of TNs will transform the real-time capabilities of the OPC UA, which in turn will provide for extended functionalities of the IoT platforms (Zezulka et al., 2019). Moreover, CPMT offers advanced connectivity. As such, a variety of networks can be applied to achieve reliable and efficient communications among the physical device, the digital model, and the human operator. To acquire real time feedback from CNC controllers, communication protocols such as Profinet, EtherCAT, Powerlink, RS-232 and RS-485 may be implemented. Next, the collection of data can be achieved through communication protocols such as Ethernet, ZigBee, and Bluetooth. For this reason, cheap microcontrollers such as Arduino or Raspberry Pi can be used (Liu et al., 2018). In Table 2, the most common communication architectures under the Industry 4.0 framework are listed, at the machine-shop level. Whereas, in Table 3 the communication architectures at a Factory level are presented.

Table 2 Machine Tool 4.0 Communication Architectures

Complete Data dictionary
All Data Items are Time Stamped (UTC).
Uses todays Internet standards (HTTP / XML)
Common Language
Implied Semantics
Better Streaming Analytics
More secure IoT protocol

Table 3 Factory Wide Communications

Unified Communications Framework
High Level Flexible, generic data model
Support for Binary, Hybrid, or Web Services
Interoperability
Service Oriented
Platform Independence
High Availability

Machine Tool Cyber Twin (MTCT): The MTCT consists of four main modules namely, the Data fusion, the Information model, the Intelligent algorithms, and the Database.

Data fusion: 1) Clean and preprocess of raw data to extract useful information, 2) Real-time data from Machine Tool 4.0 and DAQs are converted into a common format and 3) Data from many sources (Sensors, RFIDs and so on) are grouped, in order to be used for the Information modelling.

Information model: The information model groups together all available data relevant to a particular component, so that the real-time manufacturing data can be manipulated and used efficiently in further research.

Intelligent algorithms: Prognostics and Health Management (PHM), process optimization and data visualization algorithms that retrieve data from the Machine Tool 4.0 and contribute to smart decision making.

Database: Categorization of real-time data into groups and provision of data into the Intelligent Algorithms.

5. Human-Machine Interaction (HMI)

Human-Machine interaction (also known as 'MMI' or Man-Machine Interaction (HMI)) is defined as interaction and communication between human users and machines in a complex environment through multiple interfaces. Since humans began constructing tools, there has been an association between humans and machines, and humans were trained to be machine operators. There is also a need for a systematic analysis and synthesis of the relationship between humans and machines. Industry 4.0 is evolving and developing thanks to a new environment where competition demands new manufacturing models focused on continuous flexibility and reconfigurability (Koren, 2006). With the advent of Industry 4.0, digitalization has played a key role in the development of smart factories. As such, Human Machine Interfaces (HMIs) combine many of the emerging technologies, including cyber-physical systems (CPS), the Internet of Things (IoT), Augmented and Virtual Reality (AR & VR respectively), Simulation and Digital Twins (Mourtzis, 2020). The manufacturing sector is undergoing a significant transformation, made possible by IT and related smart technologies such as Cloud computing. Cloud computing is one of the main enablers for the manufacturing sector, as it can change the conventional manufacturing business model, help to match product creativity with business strategy, and build smart factory networks that promote successful collaboration. Towards that end, in Cloud computing everything is treated as a service (i.e. XaaS). As presented in Figure 9, every service is defined in a layer (i.e. Software as a Service – SaaS; Platform as a Service – PaaS and Infrastructure as a Service (IaaS)).

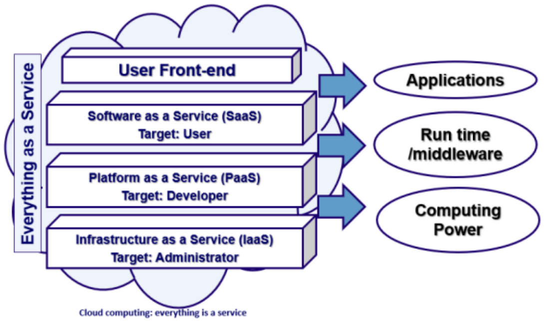


Figure 7 Everything as a Service structure of Cloud Computing (Adapted from Xu (2012))

As presented by Lee et al. (2015) the CPS has a 5-c architecture, with 5 different levels: Configuration, Cognition, Cyber, Conversion, and Connection. The key characterization of this new type of system is the change from centrally regulated to decentralized. Industry 4.0 is based on the idea of smart goods because of their adaptiveness. Three stages describe the evolution of CPS. Specifically, there are three enabling technologies implementing the 5 architecture in all its phases: integrated sensors, actuators, and decentralized intelligence. Furthermore, the Cyber-Human System (CHS) including some consideration of how to incorporate the human aspect and how the human element is essential at the higher levels is presented in Figure 10.

It has to be mentioned that the operations that are considered difficult to establish at the cyber level are the ones that humans naturally perform, and those that are inherent in the cyber world are the ones that need the most attention. Furthermore, in comparison to CPS, at each stage, CHS has the capacity to feedback data, a human worker has an inherent intelligence that can be naturally leveraged for self-adaptive, corrective, and preventive behavior.

The CHS configuration level serves as the supervisory control to ensure that the decisions taken at the cognition level are followed and the human worker takes corrective or adaptive behavior. Therefore, human-machine interaction has improved dramatically over the years and accomplished a great deal of innovation in Industry 4.0 that can be explained thanks to the key pillars of the Fourth Industrial Revolution such as Big data and analytics, Robot-assisted production, Self-driving logistics vehicle, AR and additive manufacturing.

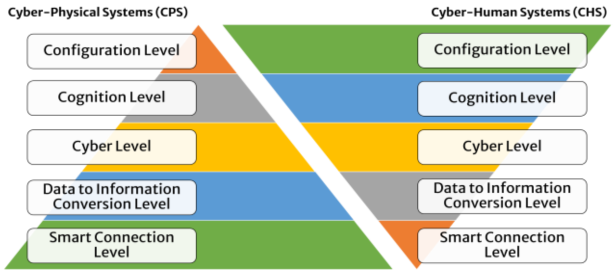


Figure 8 The CHS framework compared to the CPS (Adapted from Krugh & Mears, 2018).

6. The Automation in Manufacturing Cells

The most successful way to achieve flexible production and manufacturing systems is by product variety management (ElMaraghy et al., 2013). As this is not always feasible, two elements of production processes must be reconfigured, namely their ability to manufacture various goods, and their production efficiency as well (Koren Y., Shpitalni M., 2010). A Flexible Manufacturing System (FMS) Model was adapted from the literature and presented by Chryssolouris (2006). This FMS consisted of five five-axis machining centers, three Automated Guided Vehicles (AGVs), an automatically control washing station, a Coordinate Measuring Machine (CMM), two material review stands for on-demand part inspection, one tool pre-set and load area and two pallet carousels, with each one containing two load/unload stations (Mourtzis D. and Doukas M., 2014). An extended version of this paper is the review paper that investigates significant historical developments in the development of simulation technology and manufacturing systems and the study of recent industrial and research strategies in key fields of manufacturing. It explains how the shift towards digitalized manufacturing in the sense of the 4th Industrial Revolution influenced simulation in the design and operation of manufacturing systems and discusses the new approaches that have emerged in the literature (Mourtzis D., 2020).

Koren and Shpitalni (2010) have introduced Reconfigurable Manufacturing Systems (RMS) as a solution that incorporates both Dedicated Manufacturing Lines throughput and Flexible Manufacturing Systems versatility. Accordingly, the production method may be reconfigured if it is built in such a way that the physical framework can be modified easily, and if it has been constructed for the family of parts instead of the product. Although the solutions proposed above are primarily inspired by machining systems, they are generally applicable to assembly systems, known as Flexible Assembly Systems (FAS). Research on achieving reconfigurability for assembly systems has mostly centered on the workstation and cell stage. Work on interoperability with ease of reconfiguration of the control system has been carried out under the phrase 'plug and produce' (Engel et al., 2016). A short summary of recent RAS research approaches is presented by (Bi Z.M. et al., 2007; Harrison et al., 2007).

7. The Social Factory

As defined by Kassner et al., (2017) and Romero et al., (2017), the Social Factory is "a live enterprise social network with powerful middleware and analytics backend to improve the connection between social operators, social machines and social software systems working together in a smart production environment, and the data created within the networking process towards a sustainable learning factory". A high-level social factory architecture is presented in a detailed manner by Romero et al. (2016). As presented in Figure 11, a Social Factory consists of the Machine 4.0 equipment and the Operators of this smart equipment, named as Operator 4.0. Moreover, the enhanced sensors should have the physical ability to collect data from the environment (by vision, smell, sound, touch, vibration) and the ability to selectively perceive it.

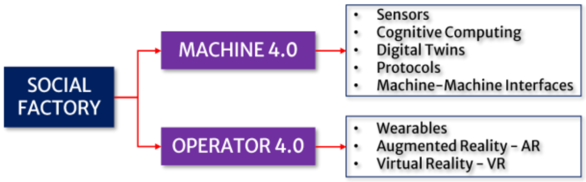


Figure 9 Structure of Social Factory (Adapted from Kassner et al., (2017) and Romero et al., 2017)

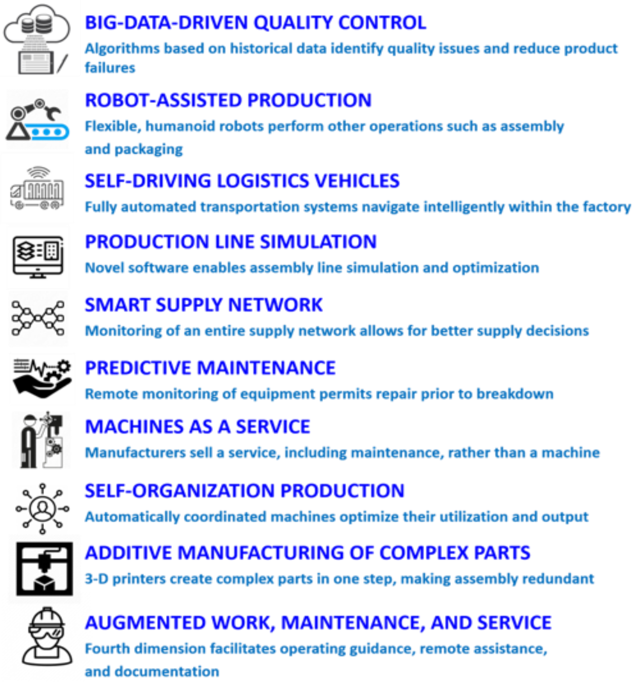
8. Concluding Remarks and Outlook

Technology can help employees stay in or return to the workforce. The comprehensive report by Lorenz M. et al. (2015a) predicts a net increase of approximately 350,000 jobs in Germany by 2025. Increased use of robotics and computerization would reduce the number of assembly and manufacturing workers by approximately 610,000. However, it is estimated that more than 960,000 new jobs, especially in IT and data science will be developed. In order to effectively implement Industry 4.0, businesses need to retrain their employees, reshape their business models, and build systematic approaches to recruitment and workforce planning. Moreover, education frameworks should contribute to closing the gap in Information Technology (IT) skills by the provision of a wider broad of set of skills. Next, Governments should explore ways to strengthen the central coordination of initiatives to encourage job growth and innovation. The advances in technology that underlie Industry 4.0 will reshape the business and economic landscapes over the next 10 to 15 years. Therefore, the ten most important areas where Industry 4.0 will transform the workforce in the coming years are compiled in Figure 12. The following examples of each use case highlight the implementation possibilities and the workforce consequences.

- Big-Data-Driven Quality Control
- Robot-Assisted Production
- Self-Driving Logistics Vehicles
- Production Line Simulation
- Smart Supply Network
- Predictive Maintenance
- Machines as a Service
- Self-Organizing Production
- Additive Manufacturing of Complex Parts
- Augmented Work, Maintenance, and Service

To summarize, manufacturers can generate revenue growth through the integration of one or more of the following routes: a) Making more flexible production lines, robotics, and 3-D printing with higher customization levels. b) Implementing business models such as "machine as a service", c) Deployment of Augmented Reality (AR) in the field for improving after-sales operation and to develop new services and d) Expanding efforts to meet the increased demand for Industry 4.0 technologies such as autonomous robots.

The adoption rate of technological innovations would lead to substantial productivity increases, thus reducing the number of workers needed to achieve a given level of production. Although some jobs will be lost, there is a substantial increase in the degree of interaction between humans and machines. At the industry level, the increasing demand for intelligent machinery would cause the manufacturers of this equipment to increase their workforce by approximately 6%. By comparison, the advent of robotics would restrict job gains for the automotive industry and for producers of manufactured metals. At the same time, robotics, and other applications, including predictive maintenance and augmented reality, will also allow manufacturers to deploy new business models that promote the creation of jobs (Lorenz M. et al., 2015a).



BIG-DATA-DRIVEN QUALITY CONTROL
Algorithms based on historical data identify quality issues and reduce product failures

ROBOT-ASSISTED PRODUCTION
Flexible, humanoid robots perform other operations such as assembly and packaging

SELF-DRIVING LOGISTICS VEHICLES
Fully automated transportation systems navigate intelligently within the factory

PRODUCTION LINE SIMULATION
Novel software enables assembly line simulation and optimization

SMART SUPPLY NETWORK
Monitoring of an entire supply network allows for better supply decisions

PREDICTIVE MAINTENANCE
Remote monitoring of equipment permits repair prior to breakdown

MACHINES AS A SERVICE
Manufacturers sell a service, including maintenance, rather than a machine

SELF-ORGANIZATION PRODUCTION
Automatically coordinated machines optimize their utilization and output

ADDITIVE MANUFACTURING OF COMPLEX PARTS
3-D printers create complex parts in one step, making assembly redundant

AUGMENTED WORK, MAINTENANCE, AND SERVICE
Fourth dimension facilitates operating guidance, remote assistance, and documentation

Figure 10 Use Cases showing the effects of Industry 4.0 on the Workforce (Adapted from (Lorenz M. et al., 2015b))

References

Benotsmane, R., Kovács, G. and Dudás, L. (2019). Economic, Social Impacts and Operation of Smart Factories in Industry 4.0 Focusing on Simulation and Artificial Intelligence of Collaborating Robots. Social Sciences, 8(5), 143. DOI: https://doi.org/10.3390/socsci8050143

Bi, Z.M., Wang, L. and Lang, S.Y. (2007). Current status of reconfigurable assembly systems. IJMR, 2(3), 303-328. DOI: https://doi.org/10.1504/IJMR.2007.014727

BCG Analysis (2020). Embracing Industry 4.0 and Rediscovering Growth, Available at: https://www.bcg.com/capabilities/operations/embracing-industry-4.0-rediscovering-growth.aspx (Accessed 15 October 2020)

Bogue, R. (2018). Exoskeletons–a review of industrial applications. Industrial Robot: An International Journal. 45(5), 585-590, DOI: https://doi.org/10.1108/IR-05-2018-0109

Bruckner, D., Stanica, M.P., Blair, R., Schriegel, S., Kehrer, S., Seewald, M. and Sauter, T. (2019). An Introduction to OPC UA TSN for Industrial Communication Systems, Proceeding of the IEEE, 107(6), 1121-1131, DOI: https://doi.org/10.1109/JPROC.2018.2888703

Chen, J., Yang, J., Zhou, H., Xiang, H., Zhu, Z., Li, Y., Lee, C.H. and Xu, G. (2015). CPS Modeling of CNC Machine Tool Work Processes Using an Instruction-Domain Based Approach, Engineering, 1(2), 247-260, DOI: https://doi.org/10.15302/J-ENG-2015054

Chryssolouris, G. (2006). Manufacturing Systems: Theory and Practice, 2nd ed. Springer New York, DOI: https://doi.org/10.1007/0-387-28431-1

CISCO, Making Machines More Connected and Intelligent. White Paper, 2015, Available at: https://www.cisco.com/c/dam/en/us/solutions/collateral/industry- solutions/C11-735862.pdf

De Looze, M. P., Bosch, T., Krause, F., Stadler, K. S., & O'Sullivan, L. W. (2016). Exoskeletons for industrial application and their potential effects on physical work load. Ergonomics, 59(5), 671-681, DOI: https://doi.org/10.1080/00140139.2015.1081988

Digital Thread for Manufacturing. 2020. Available Online: https://www.steptools.com/sln/thread/ (Accessed 15 October 2020).

ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schönsleben, P., Tseng, M. and Bernard, A. (2013). Product variety management. CIRP Annals – Manufacturing Technology 62 (2), 629–652. DOI: https://doi.org/10.1016/j.cirp.2013.05.007

Gazzaneo, L., Padovano, A., Umbrello, S. (2020). Designing Smart Operator 4.0 for Human Values: A Value Sensitive Design Approach. Procedia Manufacturing, 42, 219-226, DOI: https://doi.org/10.1016/j.promfg.2020.02.073

Gkournelos, C., Karagiannis, P., Kousi, N., Michalos, G., Koukas, S. and Makris S. (2018). Application of wearable devices for supporting operators in human-robot cooperative assembly tasks. Procedia CIRP, 76, 177-182, DOI: https://doi.org/10.1016/j.procir.2018.01.019

Guerreiro, B.V., Lins, R.G., Sun, J. and Schmitt, R. (2018). Definition of Smart Retrofitting: First Steps for a Company to Deploy Aspects of Industry 4.0. Advances in Manufacturing. Lecture Notes in Mechanical Engineering: Springer, 161-170. DOI: https://doi.org/10.1007/978-3-319-68619-6_16

Jeon, B., Yoon, J., Um, J. and Suh, S.H. (2020). The architecture development of Industry 4.0 compliant smart machine tool system (SMTS). Journal of Intelligent Manufacturing. DOI: https://doi.org/10.1007/s10845-020-01539-4

Kagermann, H., Wahlster, W. and Helbig, J. (2013). Securing the future of German manufacturing industry: recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final Rep Ind 2013. 40:1–84.

Kassner, L., Hirmer, P., Wieland, M., Steimle, F., Königsberger, J. and Mitschang, B. (2017). The

Social Factory: Connecting People, Machines and Data in Manufacturing for Context-Aware Exception Escalation. DOI: https://doi.org/10.24251/HICSS.2017.202

Koren, Y. (2006). General RMS characteristics. comparison with dedicated and flexible. Reconfigurable manufacturing systems and transformable factories, 27–45, DOI: DOI: https://doi.org/10.1007/3-540-29397-3_3

Koren, Y. and Shpitalni, M. (2010). Design of reconfigurable manufacturing systems. Journal of Manufacturing Systems, 29(4), 130–141. DOI: https://doi.org/10.1016/j.jmsy.2011.01.001

Krugh, M. and Mears, L. (2018). A complementary cyber-human systems framework for industry 4.0 cyber-physical systems. Manufacturing Letters, 15 (part B), 89–92. DOI: https://doi.org/10.1016/j.mfglet.2018.01.003

Lee, J., Bagheri, B. and Kao, H.-A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters, 3(1), 18–23. DOI: https://doi.org/10.1016/j.mfglet.2014.12.001

Liu, C., Vengayil, H., Lu, Y. and Xu, X. (2019). A Cyber-Physical Machine Tools Platform using OPC UA and MTConnect. Journal of Manufacturing Systems, 51, 61-74, DOI: https://doi.org/10.1016/j.jmsy.2019.04.006

Liu, C., Vengayil H., Zhong Y. R. and Xu X. (2018). A systematic development method for cyber-physical machine tools, Journal of Manufacturing Systems, 48, 13-24, DOI: https://doi.org/10.1016/j.jmsy.2018.02.001

Liu, C. and Xu X. (2017). Cyber-physical Machine Tool – The Era of Machine Tool 4.0, Procedia CIRP, 63, 70-75, DOI: https://doi.org/10.1016/j.procir.2017.03.078

Lorenz M., Rüßmann M., Strack R., Lueth K. L., Bolle M. (2015). Man and Machine in Industry 4.0: How Will Technology Transform the Industrial Workforce Through 2025? THE BOSTON CONSULTING GROUP. Available Online: https://www.bcg.com/publications/2015/technology-business-transformation-engineered-products-infrastructure-man-machine-industry-4 (Accessed 15 October 2020).

Lorenz M., Rüßmann M., Waldner M., Engel P., Harnisch M., Gerbert P., and Justus J. (2015b). Industry 4.0: The Future of Productivity and Growth in Manufacturing. THE BOSTON CONSULTING GROUP. Available Online: https://www.bcg.com/en-gr/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries (Accessed 15 October 2020).

Lu, Y., Xu, X. and Wang, L. (2020). Smart manufacturing process and system automation – A critical review of the standards and envisioned scenarios. Journal of Manufacturing Systems, 56, 312-325, DOI: https://doi.org/10.1016/j.jmsy.2020.06.010

Mahnke, W. (2020). Information Modelling with OPC Unified Architecture Basis for standardized information models. ATP edition, 3, 58-65

Marcon, P., Zezulka, F., Vesely, I., Szabo, Z., Roubal, Z., Sajdl, O., Gescheidtova, E. and Dohnal, P. (2017). Communication technology for industry 4.0. Progress In Electromagnetics Research Symposium, 1694-1697, DOI: https://doi.org/10.1109/PIERS.2017.8262021

Michalos, G., Makris, S., Spiliotopoulos, J., Misios, I., Tsarouchi, P., and Chryssolouris, G. (2014). ROBO-PARTNER: Seamless human-robot cooperation for intelligent, flexible and safe operations in the assembly factories of the future. Procedia CIRP, 23, 71-76. DOI: https://doi.org/10.1016/j.procir.2014.10.079

Monostori, L. (2014). Cyber-physical production systems: roots, expectations and R&D challenges. Procedia CIRP, 17, 9–13, DOI: https://doi.org/10.1016/j.procir.2014.03.115

Mourtzis D. (2020). Simulation in the design and operation of manufacturing systems: state of the art and new trends, International Journal of Production Research, 58:7, 1927-1949, DOI: https://doi/org/10.1080/00207543.2019.1636321

Mourtzis, D., Angelopoulos, K. and Zogopoulos, V. (2019). Mapping Vulnerabilities in the Industrial Internet of Things Landscape. Procedia CIRP, 84, 265-270, DOI: https://doi.org/10.1016/j.procir.2019.04.201

Mourtzis, D. and Doukas, M. (2014). The evolution of manufacturing systems: From craftsmanship to the era of customisation, Design and Management of Lean Production Systems, IGI Global, 1-29, DOI: http://dx.doi.org/10.4018/978-1-4666-5039-8

Mourtzis, D, Doukas, M, Bernidaki, D. (2014). Simulation in Manufacturing: Review and Challenges. Procedia CIRP, 25, 213–229, DOI: https://doi.org/10.1016/j.procir.2014.10.032

Mourtzis, D., Gargallis, A. and Zogopoulos, V. (2019). Modelling of Customer Oriented Applications in Product Lifecycle using RAMI 4.0, Procedia Manufacturing, 28, 31-36, DOI: https://doi.org/10.1016/j.promfg.2018.12.006

Mourtzis, D., Milas, N. and Athinaios, N. (2018). Towards Machine Shop 4.0: A General Machine Model for CNC machine-tools through OPC-UA, Procedia CIRP, 78, 301-306, DOI: https://doi.org/10.1016/j.procir.2018.09.045

Mourtzis, D., Milas, N., Vlachou, E. and Liaromatis, J. (2018). Digital transformation of structural steel manufacturing enabled by IoT-based monitoring and knowledge reuse. International Conference on Control, Decision and Information Technologies CoDIT'18. 295-301, DOI: https://doi.org/10.1109/CoDIT.2018.8394874

Mourtzis, D., Siatras, V. and Zogopoulos, V. (2020). Augmented reality visualization of production scheduling and monitoring. Procedia CIRP, 88, 151-156. DOI: https://doi.org/10.1016/j.procir.2020.05.027

Mourtzis, D. and Vlachou, E. (2018). A cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance, Journal of Manufacturing Systems, Volume 47, 179-198, DOI: https://doi.org/10.1016/j.jmsy.2018.05.008

Mourtzis, D., Vlachou, E. and Milas N. (2016). Industrial Big Data as a result of IoT adoption in Manufacturing. CIRPe 2016, 5th CIRP Global Web Conference, Open Access Procedia CIRP, 55, 290-295, DOI: http://dx.doi.org/10.1016/j.procir.2016.07.038

Nicolae, A., Korodi, A. and Silea, I. (2019). Identifying Data Dependencies as First Step to Obtain a Proactive Historian: Test Scenario in the Water Industry 4.0. Water, 11(6), DOI: https://doi.org/10.3390/w11061144

Product overview of DMG MORI. 2020. Available Online: https://us.dmgmori.com/products (Accessed 15 October 2020).

PWC. (2018). Workforce of the future: The competing forces shaping 2030. Available Online: https://www.pwc.com/gx/en/services/people-organisation/workforce-of-the-future/workforce-of-the-future-the-competing-forces-shaping-2030-pwc.pdf (Accessed 15 October 2020)

Romero, D., Bernus, P., Noran, O., Stahre, J. and Fast-Berglund, Å. (2016). The operator 4.0: human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems. IFIP international conference on advances in production management systems. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-51133-7_80

Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fast-Berglund, Å. and Gorecky, D. (2016). Towards an Operator 4.0 Typology: A Human-Centric Perspective on the Fourth Industrial Revolution Technologies, Int Conf Comput Ind Eng Proceedings.

Romero, D., Wuest, T., Stahre, J. and Gorecky, D. (2017). Social Factory Architecture: Social Networking Services and Production Scenarios Through the Social Internet of Things, Services and People for the Social Operator 4.0. 265-273.DOI: http://doi.org/10.1007/978-3-319-66923-6_31

SAP White Paper. (2017). Industry 4.0: What's Next: An SAP Point of View, Available Online: https://www.iotjournaal.nl/wp-content/uploads/2018/01/Industry_4_0_What%E2%80%99s_Next.pdf (Accessed 15 October 2020)

Schaeffler, DMG MORI, (2020) Available Online: https://en.dmgmori.com/products/technology-partner/schaeffler (Accessed 15 October 2020)

Schmied, S., Grossmann, D., Mueller, R.K., Mathias, S.G. and Jumar, U. (2020). Creation and management of Information Models for existing production systems. AT-Automatisierungstechnik, 68(5), 325-336, DOI: https://doi.org/10.1515/auto-2020-0021

SCM World/Cisco "Smart Manufacturing & the Internet of Things 2015" survey of 400 Manufacturing Business Line Executives and Plant Managers across 17 vertical industries

Zezulka, F., Marcon, P., Bradac, Z., Arm, J. and Benesl, T. (2019). Time-Sensitive Networking as the Communication Future of Industry 4.0, IFAC-PapersOnLine, 52(27), 133-138, DOI: https://doi.org/10.1016/j.ifacol.2019.12.745

Zhu Z. and Xu X. (2020). User-centered information provision of Cyber-Physical Machine Tools, Procedia CIRP, 93, 2020, 1546-1551, DOI: https://doi.org/10.1016/j.procir.2020.04.091