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Assessment model for industrial companies to define the maturity level of Industry 4.0 implementation

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ABSTRACT

The academic work focuses on the realization of an Industry 4.0 assessment tool for industrial realities. By means of a systematic literature review, whose aim consists in the screening of the Industry 4.0 related academic landscape, a total of 42 Industry 4.0 concepts are ascertainable, which form the theoretical backbone of the assessment tool. In relation to each concept, five maturity levels are determined with the intent of illustrating the potential Industry 4.0 maturity degree of the analyzed companies. For the assessment purpose, two parameters play an essential role, namely the current and the desired entrepreneurial level of maturity with respect to the Industry 4.0 concepts. To specify the relevance of the gap between present and future maturity stage, a weight, which varies according to the industrial sector in which the company is acting, is attributed to the value. The described model structure is brought into being through the support of the software Excel.

The assessment model calls for a guided implementation approach that requires the guidance of an Industry 4.0 expert and the participation of a company representative. Within a time period of two hours, the identification as well as prioritization of the Industry 4.0 concept gaps is performed. The two companies that are object of study of the assessment obtain a recommendation for action concerning Industry 4.0 concepts, which functions as base for a successful Industry 4.0 strategy implementation.

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NOMENCLATURE

3D. Three-Dimensional.

3DP. Three-Dimensional Printing.

ACATECH. Deutsche Akademie der Technikwissenschaften.

AFD. Automatic Fault Diagnosis and warning.

AHP. Analytic Hierarchy Process.

AIDA. Analisi Informatizzata delle Aziende Italiane.

ALU. Automatic Loading and Unloading systems.

AM. Additive Manufacturing.

ANSI. American National Standards Institute.

ASTM. American Society for Testing and Materials.

ATHENA. Advanced Technologies for Interoperability of Heterogeneous Enterprise Networks and their Applications.

C4ISR. Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance.

CAD. Computer Aided Design.

CFD. Computational Fluid Dynamics.

CFFJS. Continuous Flow Flexible Job Shop.

CIMO. Continuous Intensity Map Optimization.

CP. Cover Period.

CPS. Cyber-Physical Systems.

DIN. Deutsches Institut für Normung.

DLT. Digital Logistic Tracking system.

DMD. Direct Metal Deposition.

DMS. Distributed Manufacturing System.

DT. Document Type.

EBM. Electron Beam Melting.

EIF. European Interoperability Framework.

EOQ. Economic Order Quantity.

EPC. Electronic Product Code.

ERP. Enterprise Resource Planning.

FDM. Fused Deposition Modelling.

FEA. Finite Element Analysis.

FP. Firmly Pertinent.

HMS. Human-Machine System.

HMS. Holonic Manufacturing System.

HPD. High-Precision online testing and inspection system.

HRM. High Resolution Management.

IaaS. Infrastructure as a Service.

IDABC. Interoperable Delivery of European eGovernment Services to public Administrations, Business and Citizens.

IEC. International Electrotechnical Commission.

IIS. Integrated Information Systems.

IJP. Ink Jet Printing.

IOS. International Organization for Standardization.

IoT. Internet of Things.

ITU. International Telecommunication Union.

L. Language.

LBM. Leveled and Balanced Mixed flow production.

LISA. Line Information System Architecture.

LOM. Laminated Object Manufacturing.

LSMCS. Large Scale Machine Coordination Systems.

MAS. Multi Agent System.

MBD. Multi-Body Dynamics.

MES. Manufacturing Execution System.

MP. Moderately Pertinent.

NC.	Numerical Control:
NP.	Non-Pertinent.
NPV.	Net Present Value.
NSF.	National Science Foundation.
PaaS.	Platform as a Service.
PD.	Publication Database.
PLCs.	Programmable Logic Controllers.
PLM.	Product Lifecycle Management.
POS.	Parameters Optimization System.
PRISMA.	Preferred Reporting Items for Systematic review and Meta-Analysis.
PSA.	Product-Service Architecture.
RFID.	Radio Frequency Technology.
RIA.	Robotic Industries Association.
RM.	Rapid Manufacturing.
RMP.	Real-time Monitoring system of Production process.
RP.	Rapid Prototyping.
RT.	Rapid Tooling.
SA.	Subject Area.
SaaS.	Software as a Service.
SAG.	Strategic Advisory Group.
SACRA.	Selective Compliance Assembly Robot Arm.
SBF.	Smart Behavioral Filter.
SFP.	Science Fiction Prototyping.
SIAT.	System Invariant Analysis Technology.
SLM.	Selective Laser Melting.
SLNA.	Systematic Literature Network Analysis.
SLS.	Selective Laser Sintering.
SS.	Search String.

ST.	Source Type.
STC.	Source Type Completeness.
STL.	STereo Lithography.
TBM.	Technical Management Board.
TPS.	Toyota Production System.
VC.	Virtual Commissioning.
VE.	Virtual Enterprise.
VEO.	Virtual Engineering Object.
VEP.	Virtual Engineering Process.
WMS.	Workload Management System.
WSN.	Wireless Sensor Network.

Chapter 1

INTRODUCTION

The introductory section, which is composed of three main parts, aims at providing a concise outline of the master thesis' content. The introduction describes briefly the current situation including challenges that companies have to face in order to remain in business in the long run. Subsequently, the motivations, which led to the elaboration of the industrial assessment model to define the maturity level of Indus-try 4.0 implementation, are cited and explained. To complete the prefatory section, the structure of the presented work is succinctly presented.

1.1 Introduction

The evolution of industry was characterized by radical transformations that put enormous pressure on companies. Each portion of industrial history implied several challenges, which had to be comprehended, analyzed and lastly overcome. At this current time, the scenario has remained unchanged. The complexity emerges due to the simultaneous oppositeness and connectedness related to the requirements, which have to be satisfied. In other words, companies have to create and offer top-quality products at the lowest price as well as in the shortest time in order to fulfill the customer expectations and requirements.

In addition, unstable market dynamics provoked by novel social, environmental, economic and technological trends forces enterprises to fight for survival in global markets, which are affected by a fierce competition. Resource scarcity, expensive labor forces and the rise of the so-called BRIC-countries are only few of them, which have become exceptionally noteworthy. Currently, one natural question arises: How can the European Industry, which suffers particularly from the current condition, cope successfully with such substantial difficulties?

Given the situation outlined above, it is by means straightforward that a radical reorientation of the total industry is indispensable. Companies have to shape their value chain in a way that allows them to maximize its flexibility, responsiveness and agility. First off, physical and digital structures have to be reorganized under consideration of these principles [1]. The unprecedented situation associated to the industrial context, which is significantly characterized by the presence of the digitalization, draws the beginning of a new industrial era denominated as the fourth industrial revolution. Tracing the industrial history back into the year 2011, three personages deriving from the industrial, political as well as academic sphere, namely Prof. Dr. Henning Kagermann, Prof. Dr. Wolf-Dieter Lukas and Prof. Dr. Wolfgang Wahlster, proclaimed the birth of the strategic initiative "Industrie 4.0" at the Hannover fair in Germany. According to the pool of experts, Cyber-Physical Systems (CPS) as well as their interconnectedness, which is referred to as Internet of Things (IoT), will occupy a central position within the industrial realm [2].

This spectacular event had a profound impact on the worldwide industrial scene. As one might expect, nearly all the industrialized nations reacted to the significant occurrence by demonstrating financial commitment into Industry 4.0 related projects. In particular, Germany, which already possess a stable and competitive industry, has assumed the pioneering role. Anyway, other continents, like Asia and USA, even do not sit on their hands and try to take accurate measures.

1.2 Motivation

The proclamation of the fourth industrial revolution shocked the industrial world. Suddenly almost every modern enterprise aspired to become a proper "Industry 4.0" factory. In the industrial environment, a curious feeling grew. At a first glance, Industry 4.0 was not really perceived as an opportunity, but more as a challenge. The clouded mood was attributable to the fact that companies had serious difficulties in comprehending the significance belonging to the term itself. The industrial realm completely lay in the dark so that preparation and execution of concrete implementation steps could not be initiated.

Only few years later, research institutions were able to render indispensable assistance through the publication of guidelines, which for the first time covered the topic associated to the concrete realization of the concept. One of the remarkable works, titled "Guideline Industry 4.0- Guiding principles for the implementation of Industry 4.0 in small and medium sized businesses", which was presented in the VDMA forum, offered an "Industry 4.0-toolbox" that should provide first guidance in the challenging reorientation process [3]. The presented solution approaches, which demand the execution of substantial internal modifications, touch mainly two dimensions, which are represented by the product-sphere and the production-sphere. In particular, the combination of a wide range of harmonizing technologies connected to both realms, should allow the enterprises to turn the industrial redirection to good account. The supplied toolbox was perceived as an acceptable starting base, which was characterized by the exhibition of conspicuous gaps.

This fact induced researchers, to exploit the elaborated directives as foundation for the development of further models. Schumacher et al. take a relevant step in this direction through their publication "A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises" [1]. The depicted model targets the determination of the readiness for the introduction of Industry 4.0 related measures. Compared with former works, the degree of completeness of the model is enhanced through the inclusion of several technological and organizational aspects, which are categorized into nine dimensions and 62 specific items [1]. However, there is still room for further improvements. At this point, the presented result of the master thesis comes into play with the purpose to pass to an additional stage in the evolution of Industry 4.0 related assessment models. It opens doors to new and enriched evaluation possibilities that are not anymore addressing a problem of readiness of enterprises, but one affiliated to the maturity level associated to the Industry 4.0 implementation. In other words, the model's objective is to signalize to companies the feasibility, the commitment, the presence and the related current progress status of several reindustrialization phases.

The fundamental motivation that lead to the development of the subsequent work can be found in the fact that the industrial realm calls for instruments that help to maintain or gain the vital competitive edge in fiercely competitive markets. Enterprises, which at present are reliant on the fourth industrial revolution and their triggered effects, have to identify the implementation grade and the needs for a specific Industry 4.0 measure. The root cause can be explained quite straightforwardly: improvements can be achieved if and only if the measurability is provided.

1.3 Outline

The academic work can be subdivided into seven parts, which are represented by the introduction, the state of the art, the realization of an assessment tool for Industry 4.0 implementation, the validation of the assessment model in real industrial companies, outlook or further research and optimization and in the conclusion.

The prefatory section, which consists of three parts, targets at providing a plain overview of the master thesis' substance. The introduction depicts concisely the present situation, which is characterized by numerous dares that enterprises have to face in order to maintain or enhance the degree of competitiveness. Afterwards, the motivations, which induced the creation of the industrial assessment model to evaluate the maturity level of Industry 4.0 implementation, are taken into consideration. To finalize the introductory section, the structure of the presented work is exhibited.

The second section of the master thesis, which can be considered as the theoretical backbone of the academic work, in a first step, aims at providing a thorough overview of the industrial revolution history as well as the definitions of Industry 4.0 and associated terms. Ensuing, the fundamentals of Industry 4.0 are scrutinized. Especially, the delineation of concepts like CPS, IoT, Big Data, Smart Products, Connectivity, Additive Manufacturing, Automation, Digitalization, Work 4.0 as well as Safety and Security are incorporated. The presence of a robust level of knowledge permits to pass to the individuation of opportunities and threats associated to the last industrial revolution. To conclude the section dedicated to the state of the art an outline of existing assessment models and maturity stages models is realized.

The core part of the entire master thesis is represented by the third and fourth chapter. Actually, the development of an applicable assessment tool for Industry 4.0 is performed. Initiating with the research methodology and approach, in which a solid theoretical fundament is determined, the systematic literature review is conduced. The essentiality of the literature review straightforwardly catches the eye by observing the related outcome. In concrete, the analysis allows to individuate a valuable record collection from which elements epitomizing individual components of the assessment model, are extracted. The accomplishment of the illustrated passage and the definition of dimensions and categories of Industry 4.0 concepts, enable the conceptional realization of the assessment model. The pre-requisite for applicability of the model within industrial environment is ensured by means of the translation of the conceptual model into an Excel-based assessment model.

The fifth section of the master thesis puts emphasis on the validation of the assessment model in two South Tyrolean industrial enterprises. The assessed entrepreneurial realities categorizable as SMEs operate in distinct industrial sectors, which are epitomized by the production of food products and the manufacture of machinery for the construction sector. The assessment results of both enterprises are presented and interpreted briefly.

The penultimate chapter of the master thesis is devoted to the determination of progressive scientific investigations related to the Industry 4.0 assessment tool. Improvement suggestions associated with the structure and the content of the instrument are cited with the intent of ameliorating its applicability. In addition, the feasibility of fundamental mutations including the abolishment of the guidance supplied by means of the interviewer with the aim of creating an Industry 4.0 implementation database, is discussed.

The master thesis is finalized with the conclusion, which is entailed in the seventh chapter.

Chapter 2

STATE OF THE ARTS

This section of the master thesis, in a first step, aims at providing a complete overview of revolutions in the industrial history as well as the definitions of Industry 4.0 and related terms. Subsequently, the fundamentals of Industry 4.0 are treated in detail. In particular, the description of concepts or technologies like CPS, IoT, Big Data, Smart Products, Connectivity, Additive Manufacturing, Automation, Digitalization, Work 4.0 as well as Safety and Security are introduced. The creation of a solid knowledge base allows to pass to the determination of strengths, weaknesses, opportunities and threats belonging to fourth industrial revolution. To complete the part devoted to the state of the art an outline of existing assessment models and maturity stages models is presented.

2.1 The four industrial revolutions

The first industrial revolution induced a crucial turnaround of the human history that altered nearly every aspect of the daily life. Starting from 1760 up to the year 1840 production environments and in particular manufacturing was destined to undergo profound changes [4]. The first nation that passed from an agriculture-based economy to an industrial one was Great Britain followed by several European countries like Belgium, France and Germany [5]. Since the dawn of the revolution, it has been clear that the industrialization will affect features, which at first glance could seem not significantly related to the technological realm. Two respective examples, which are represented by socioeconomic and cultural features can be mentioned. The technological variation comprised mainly the usage of new elementary materials, above all iron and steel, and innovative typologies of energy sources, which can be classified into fuel and motive power [6].

Not only materials and energy sources, but also inventions and the new organization of work must be counted to the fundamental pillars of the industrial revolution. Due to the fact that the textile production and trade was dominating the economic landscape of Great Britain, it was the first to benefit from the effects of the revolution [7]. The “spinning jenny”, the first multiple-spindle machine for spinning wool or cotton, and the so-called “factory system”, which initiated a labor division and the resulting specialization of workforces, gave life to the first modern industry [8]. The traditional figure of the worker was modified dramatically through the acquisition of unedited skills that did not include the ability to work with hand tools, but to operate a machine. Nevertheless, other important technical advances in the communication and transport were provoked by inventions such as the telegraph or the radio as well as the locomotive or the steamship [6]. Even if technical features were typically underlined in history books, it is important to notice that relevant socioeconomic and cultural mutations occurred. In particular, the balance within the society was put into discussion by distributing wealth over a wider range of society levels [9]. The shift from land as a source of prosperity to industry, compromised economic privileges as a birthright among the nobility, banking or merchant families and allowed common people to reach actually high level of wealth. In addition, the concentration of working forces around industrialized areas leads to the creation or the growth of cities [10].

After a brief shortfall in innovations in the mid of the 19^{th} century, the industrial realm experienced once again an inventive upturn. In spite of significant similarities with the initial industrial revolution, the second, also known as technological revolution, took place between 1870 and 1914 [11]. This short piece of history was characterized by a new and stronger acceleration of the industrialization process caused by technological discoveries, which include lighter materials, like alloys and synthetics, and the implementation of a new energy source, namely the electricity [12]. Parallel to this development, the machine tool industry evolved and the importance of new theories came to light. Firstly, the scientific management or Taylorism has to be mentioned. It concentrates on the analysis of workflows and the fragmentation of jobs in order to minimize worker skills and learning times [13]. The overall aim is to achieve extraordinary high labor productivity and economic efficiency [14]. The fundamental principles of the Taylorism inspired the famous American entrepreneur, Henry Ford. He assumed a pioneer role in the global industrial scene through the development of a modern industrial system, whose focal point is composed by the principle of standardization. The first assembly lines were constructed within production sites and the fundaments for the future mass production phenomenon were laid [15]. The progress stimulated the dissemination of known transportation and communication technologies, which previously were predestined to a couple of industrial centers and triggered the first wave of globalization. Also, the owning principles of production sites experienced changes that lead to the division of belongings through the sale of ordinary shares to individuals or institutions [12]. The end of the technological revolution is forced by an event that shocked the whole world, which is represented by the first world war. Subsequently, the discontinuity of the industrial evolution was prolonged by the second world war. However, a few decades after, the industry was able to create the precondition for the following revolutionary step, namely the beginning of the information age. In this period of time firm bases for the information age were built through the realization of transistors. In addition, a highly relevant management philosophy appeared. The Toyota Production System (TPS) is perceived as the forerunner of the lean manufacturing, whose key principles are embodied by value, value stream, flow, pull and finally perfection [16].

From 1970 up to the year 2012, the third industrial revolution, or how experts prefer to term it, the digital revolution, induced the transition from mechanical and analogue technologies to digital ones. Absolutely essential was the diffusion of the digital logic technology, which includes computers and world wide web. Another pillar is represented by the mass production, followed by the mass customization, which allows to fulfill customer requirements related to products by utilizing flexible computer-aided tools [17]. The ability to combine successfully variegated elements belonging to the information technology allowed to evolve high-level automation in manufacturing due to programmable logic controllers (PLCs) and robots. The period of the third industrial revolution, similarly to the predecessors saw the birth of a new energy source that is represented by nuclear energy [18].

The last and current industrial revolution is the fourth. The Industry 4.0 era was facilitated through further development in the technological field that comprise the creation of Cyber-Physical Systems (CPS) and its networking, also called Internet of Things (IoT). The distinctive feature of the fourth industrial revolution is the ability through technology to combine digital, physical and biological realms that affect decisively a broad spectrum of industrial disciplines [19]. Figure 1 illustrates the timeline related to the four industrial revolutions.

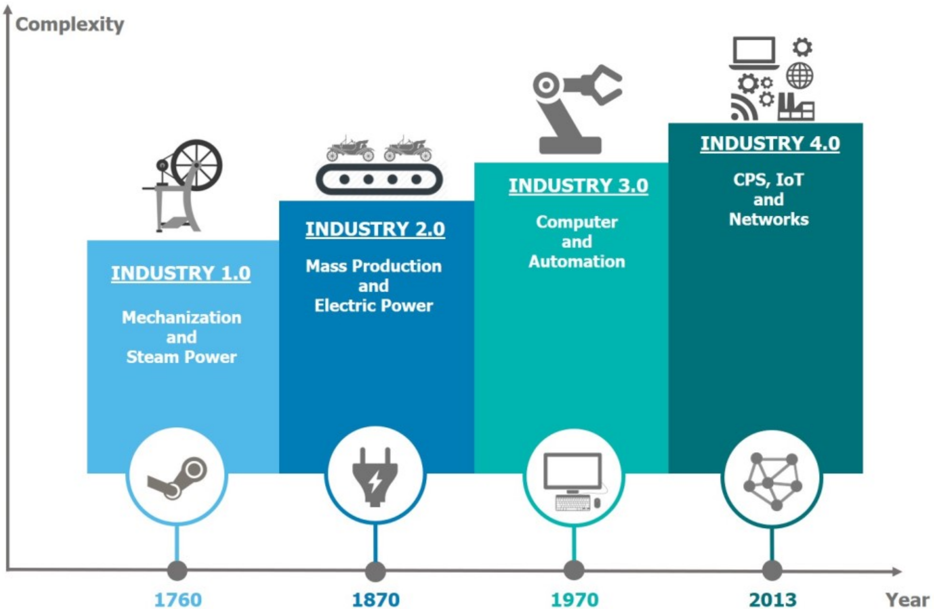

Figure 1: The timeline of the industrial revolutions (adapted from [20]).

2.2 Definition of Industry 4.0 and related terms

In this introductory paragraph, some previously mentioned terms, are defined to assure the existence of a common knowledge base that serves as fundament for the entire work. The validity of the presented definitions is guaranteed through the credibility of the selected source, which are represented by renowned institutions, innovative enterprises or experts in the treated field. The concepts that are specified are Industry 4.0, CPS, IoT, Big Data and conclusively Smart Factory.

The oldest reference to *Industry 4.0* goes back to the year 2011, in which at the Hannover Fair in Germany a pool of experts first created the term. The management board of the International Organization for Standardization (ISO) announced in the year 2015 to create an interdisciplinary strategic consultative team focusing on Industry 4.0 that cooperates tightly with the International Electrotechnical Commission (IEC) and the International Telecommunication Union (ITU) in order to generate a concise a definition of Industry 4.0. The work is still under way. For the American National Standards Institute (ANSI) Industry 4.0 "refers to the fourth industrial revolution, a new level of organization and control of the whole value chain and over the life of the cycle of products. Phases of this cycle are oriented on the demand of the individual customer and include idea, order, construction and development, the delivery of the product to the end customer, recycling, and related services" [21], whereas the Deutsches Institut für Normung (DIN) defines it as "the merging of virtual worlds with real production. This means that areas such as mechanical engineering, logistics and IT must work together smoothly - across the globe" [22].

Cyber-Physical Systems (CPS) are perceived as the enabler of the latest industrial revolution. According to the National Institute of Standards and Technology Cyber-Physical Systems Working Group, which released an initial draft, CPS are understood as "smart systems that include engineered interacting networks of physical and computational components. These highly interconnected and integrated systems provide new functionalities to improve quality of life and enable technological advances in critical areas, such as personalized health care, emergency response, traffic flow management, smart manufacturing, defense and homeland security, and energy supply and use” [23]. Also, the National Science Foundation (NSF) offers a brief explanation of CPS, which “refers to the tight conjoining of and coordination between computational and physical resources” [24].

The concept that has the strongest connection to CPS is *Internet of Things*. Indeed, either aims at enhancing the linkage between cyber and physical sphere, by exploiting the information technology. However, they possess heterogeneous focal points. While CPS concentrates on information sharing and feedback, IoT deals with connectivity and networking [25]. ISO/IEC, a notable standards development environment, where experts work in harness to define and evolve concepts related to the Information and Communication Technology (ICT), specify IoT as “an infrastructure of interconnected objects, people, systems and information resources together with intelligent services to allow them to process information of the physical and the virtual world and react” [26].

The previous treated terms are particularly affiliated to *Big Data* as they generate and function with a vast volume of information. The expression Big Data is utilized in a broad range of realms, whose characteristics are exploited in variegated manners. In light of these circumstances, it is even more important to provide an accurate definition of the concept. In accordance with the ISO/IEC, Big Data can be specified as “a data set with characteristics (e.g. volume, velocity, variety, variability, veracity, etc.) that for a particular problem domain at a given point in time cannot be efficiently processed using current/ existing/ established/ traditional technologies and techniques in order to extract value” [27].

Corresponding to the DIN, the last treated concept, namely the *Smart Factory*, is perceived as the result, which is in harmony with Industry 4.0, CPS, IoT and Big Data [28]. As a matter of fact, many research institutions, but also several companies expressed their interest in the concept of Smart Factory. An example is the Fraunhofer Gesellschaft, which promotes projects related to the Smart Factory in several institutes [29]. The concept of Smart Factory is object of study also of the Daimler AG that defines it as “the centerpiece of the digitalization of the entire company. In the smart factory, the products, machines and the entire environment are networked with each other and connected to the internet. Integration of the real world into a functional, digital world enables a so-called digital twin to be created, which allows the real-time representation of processes, systems and entire production shops” [30].

Figure 2: Word cloud of Industry 4.0 and related terms (created with Wordle Word Cloud Generator).

2.3 Fundamentals of Industry 4.0 and Smart Factory

The second subsection of the part devoted to the state of the art covers the fundamentals of Industry 4.0 and Smart Factory. Relying on the introduction of ten elementary concepts or technologies, the backbone on which Industry 4.0 and the Smart Factory lean, is successively established. The mentioned elements are represented by CPS, IoT, Big Data, Smart Products, Connectivity, Additive Manufacturing, Automation, Digitalization, Work 4.0 and to conclude Safety and Security.

2.3.1 Cyber-Physical Systems: merger of digital and real world

CPS are contemplated as principal enabler and consequently as the first pillar of the Industry 4.0 fundament. Pursuant to the National Institute for Standards and Technology (NIST), CPS are specified as “co-engineered interacting networks of physical and computational components” [31]. Findings belonging to a broad range of scientific realms, which include cybernetics, mechatronics and process theory, confluence and enable the existence of such systems that are characterized by a firm interdisciplinary nature. The transformative technology strives for the amalgamation of two different worlds, which are respectively represented by the virtual and physical sphere. In order to realize the declared achievement, the system unites and exploits the full potentiality of elementary innovation areas that pertain to the information and communication technology realm, namely embedded software-intense systems and global networks [32]. The creation of embedded systems paves the way for extensive solution options that impact positively several domains. In particular, the industry benefits the most from the CPS-potential [33].

The prime industrial sub-area that demonstrates the capability of the transformative technology is unambiguously the automotive sector [34]. For the production sites and the products, CPS are of vital significance as they are capable of enhancing safety, comfort, efficiency as well as networking quality. However, other sectors exploit successfully the offered innovative performance. Medical engineering, which is characterized by continuous growth and high research and development investments, places increasingly emphasis on CPS to enable an optimal patient car. Precisely because the uninterrupted demographic change can be equated with greater demand for healthcare services, CPS-based devices, such as tele-medical patient monitoring or ambient assisted living solutions, will assume a crucial role within the mentioned sector. The medical coverage represents only one of the numerous future challenges that have to be overcome [35]. The energy industry is confronted with analog difficulties due to an enhanced energy necessity. Also, to approach this issue, CPS and their intelligent network management can function as relevant support [36].

Provided the enormous potential and the diversified operating range of CPS, researchers recognized the need for a unified system framework. The determination of the general structure of CPS should provide a universal implementation guideline especially for industrial sectors. Conventionally, the structure of CPS was categorized according to the functional elements that are respectively the sophisticated connectivity and the smart process data capacity. Provided the high degree of abstraction and the general character of this type of classification, Lee et al. propose the definition of a specific five-level CPS structure, the so-called 5C-Architecture, which should serve as concrete implementation and construction guideline [37]. Figure 3 illustrates graphically the main levels.

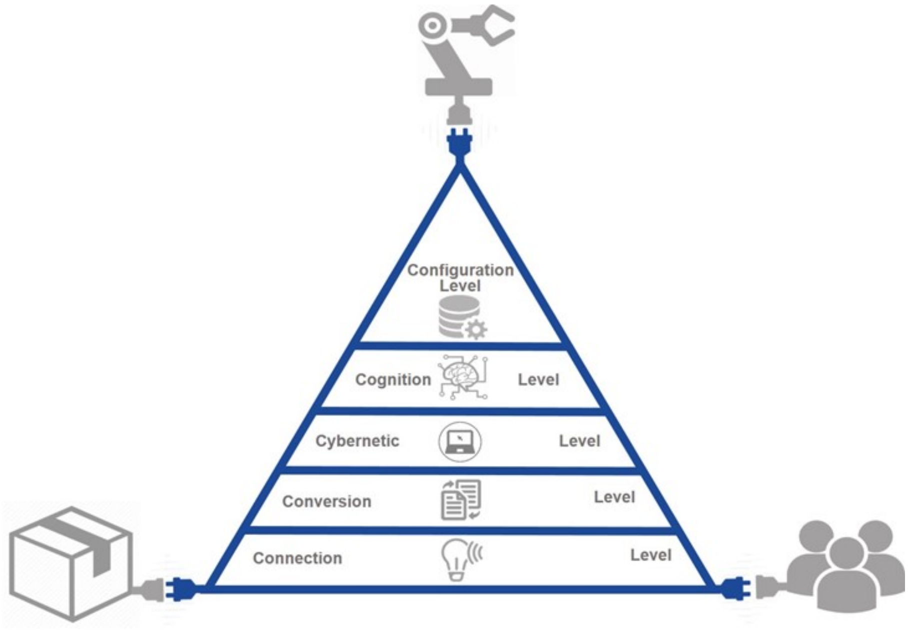

Figure 3: Cyber-physical system 5C-architecture (adapted from [19]).

The first level is composed of the smart connection. The CPS requires precise data that can be stemmed from sensors, controllers or various enterprise systems. The data collection level is succeeded by the commutation of data into information. To enable an effective extraction, the algorithm, which allows the maximization of the information content quality, has to be selected. The third level of the architecture is constituted by the cyber level; whose purpose lies in the function of pivotal information hub.

Specifically, designed methodologies have been developed by Lee et al. to gather additional information, which arise from the comparison between several machines. In the subsequent level, represented by the cognition, the human takes center stage. The user is authorized to visualize the elaborated data in form of intuitive graphics. To complete the 5C-Architecure model the final level, which is delineated by the configuration, is presented. The last named comprises a feedback process between cyber and physical sphere. By virtue of the performed control, the process of self-configuration and self-adaptability of the machinery fleet can be enabled [19]. In particular, corrective and preventive measures assume an essential role within the final stage of the architecture model.

2.3.2 Internet of Things: Information and Communication Technology

Internet of Things (IoT) is the paradigm that triggered a novel wave of development within the information era. At presence, the natural progression of the embedment related to entities or, more commonly, things within the environment have become part of normality [38]. The phenomenon affects several technologies or systems, including sensors, actuators, radio frequency technology (RFID), smartphones or CPS that according to the keynote of IoT have to be affiliated through predetermined patterns with the uppermost maxim to attain consolidated aims [39]. The accuracy of the exposed statement can be confirmed through the definition provided by the International Telecommunication Union (ITU) in the "recommendation ITU-T Y.2060", in which IoT is synthetized "as a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [40].

The considerable influence of IoT touches users that pertain to variegated domains. The behavior and habits of so-called home-users, whose daily routine is largely coined by the household and job environment, is directed by the proliferation of IoT. Concretely, this could imply the utilization of smart home systems that enable the remote control and alteration of states associated to apartments as well as the exploitation of digital on-the-job training [41]. The last example demonstrates clearly the variegated application nature of the paradigm. However, owing to the proclamation and introduction of Industry 4.0, the business as an IoT-user has mutated to the focal point of industrial research. Indeed, the European Commission decided to enclose the paradigm study in Horizon2020, which by virtue of the substantial funding availability of 80 billion € is considered the biggest EU Research and Innovation program ever, in order to stimulate the continental industrial enforcement [42].

Different industrial subfields are taken into consideration. Nevertheless, the transportation and logistics domain dominate the scene on account of an intensive commitment of IoT. As a matter of fact, each link of the supply chain can be supervised thanks to real-time data and information elaboration technologies [43]. Benefits are quite obvious: The instantaneous receipt of information allows to reduce dramatically the reaction time that provoke an enhancement of enterprise responsiveness and adaptability affiliated to market fluctuations or customer-requirements alterations. Furthermore, the transportation domain capitalizes on IoT through assisted driving and environmental monitoring technologies [43].

The connectivity of smart transportation systems allows the driver to minimize errors during the transportation process. Companies or governments that have valuable information at their disposal are able to initiate effective improvement measures that impact positively the industrial or social environment [44].

Provided that the advantages of IoT outweigh the disadvantages, researchers recognized the need for a unified reference model, which could facilitate the IoT-implementation. The reference model consists of four layers that are accompanied by two types of capabilities, namely management and security capabilities. The four layers are classified as “application layer, service support and application support layer, network layer and device layer” [45]. The primal layer is conceived as a sort of depository that enclose the existing IoT applications [45]. In order to empower various accomplishments, the second layer that can be portioned into generic support capabilities, including elaboration or storage of data, and peculiar support capabilities, which are reliant on the application character, has to be employed.

The third layer called network layer incorporates the network capability, which aims at providing operative system connectivity, and the transport capability that puts emphasis on the deliverability, control and management of IoT services. Finally, the fourth layer is presented. It is once again characterized by a dual unit construction. The device capabilities consider the direct and indirect interaction and the peculiar networking, whereas the gateway capabilities deal with the interfaces support and the protocol conversion [45].

In order to provide a complete reference model, two accessorial capabilities, namely the management and security capabilities, have to be introduced. The management capabilities cover the “traditional fault, configuration, accounting, performance and security (FCAPS) classes” [45]. The final capability typology that has to be taken into account is the security capability, which is grounded on prevention systems, whose responsibility comprises the protection of the application and network layer [45].

2.3.3 Big Data: The New Technological Frontier

The introduction of the information era brought "big" amendments to light, which affected various contexts from meteorology, physical simulations, biological and environmental research, healthcare up to finance and business [46]. Big Data is the term assigned to the phenomenon that altered almost every aspect and logic associated with data. David Reinsel, John Gantz and John Rydning, analysts at the International Data Corporation (IDC), estimated that within the year 2025 the global amount of generated data will exceed the border represented by 163ZB [47]. For comparison only, in the year 2016 the limit of 16.3ZB was reached. In other words, the data volume will experience a tenfold increase within ten years.

Straightforwardly, the notion "Big Data" illustrates concisely the circumstances that are characterized by the phenomenon. The continuous progression in the information field, which initiated 25 years ago, radically influenced and transformed the conception of data. Provided the clearly manageable data volume and their retarded availability of the past, analysts could comfortably structure and subsequently transform data into meaningful information. Several easy-to-use analytical methods could be implemented.

Unfortunately, the data explosion destroyed the convenient framework conditions of the recent scenario, which is not any longer consistent with today's reality [48]. Two characteristics of Big Data, namely the massive unstructured data-quantity and the demand for real-time analysis, lead to the present situation. However, mastering the obstacles provided by the constitution of Big Data guarantees the receipt of striking benefits.

The management consulting firm McKinsey accentuates the key role of Big Data in the enhancement of productivity, efficiency, competitiveness as well as in the generation of several customer advantages [49]. Indeed, Big Data is perceived as a frontier, which has to be transcended. In order to experience the benefits, first and foremost what stands behind the concept of Big Data has to be examined. Hence, for a better comprehension, definitions developed by different institutions and researchers are illustrated. Chen et. al, who conducted pioneering research work in the data realm, synthetizes in the paper "Big Data: A Survey" a universal specification of the concept by focusing on the affiliated difficulties. Generally speaking, "Big Data refers to datasets that could not be perceived, acquired, managed, and processed by traditional IT and software/hardware tools within a tolerable time" [50]. Several institutions still have managed to come upon a compromise in the provision of a univocal specification of Big Data.

ISO exposes the concept more extensively as "a data set with characteristics (e.g. volume, velocity, variety, variability, veracity, etc.) that for a particular problem domain at a given point in time cannot be efficiently processed using current/ existing/ established/ traditional technologies and techniques in order to extract value" [27]. The last-mentioned specification is considered as the forerunner of the so-called 4V-Architecture, in which the Big Data characteristics are respectively represented by "volume, variety, velocity and value" [51]. Figure 4 presents graphically the four Vs and the related meanings.

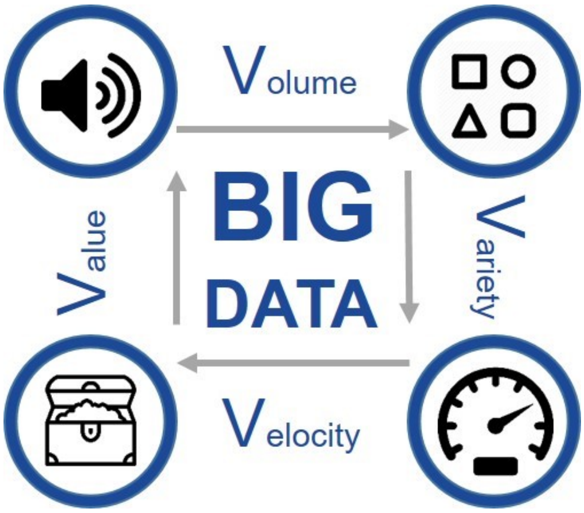

Figure 4: The 4Vs of Big Data (adapted from [51]).

The first feature, which is represented by the volume can be interpreted as a self-evident element. The enormous amount of gathered data that are generated on a daily basis at first glance could appear as an exaggeration, but through effective data analysis procedure the hidden information or pattern could be extracted. The variety pertains to the distinction of data typologies that are collected through several devices, including sensors, computers, smartphones or online platforms. The multiplicity entails the absence of a data-structure [52]. The third characteristic focuses on the significance of velocity. With the aid of fast connection, data could be transferred rapidly within the networks. Finally, the value is introduced as concluding element. Big Data conceal information treasures that could lead to astonishing benefits.

In order to increase the comprehension of Big Data, the four characteristics are employed as base to establish the categorization of Big Data. Hashem et al. stressed the fact that "five factors should be taken into consideration that are represented by the data source, content format, data stores, data staging and data processing" [53]. The notable data founts are manifold, however web and social platforms, cyber-physical systems, sensors, transactions and the IoT are ranked among the plentiful source of data. Although Big Data epitomize an unsorted nature, the content format can be subdivided into structure, semi-structured and unstructured. In order to initiate the elaboration process data first of all have to be stored. Data depots can be "document-oriented, column-oriented, graph based or key value focused" [54]. The second preparation step, which is represented by the data staging, is categorized in cleaning, normalizing and transforming. To provide the exhaustive categorization the data processing is discussed. It is represented by two typologies of process execution that could take place according to batches or in real-time [54].

2.3.4 Connectivity: Interoperability and Integration

Industry 4.0 is inextricably linked with the umbrella-term connectivity. Numerous research works lay emphasis on the relevance of the linkage-concept, which is sensed as intermediate section on which the entire fourth industrial revolution is premised on. Connectivity is a self-explanatory notion that comprise two main key factors, which are respectively represented by the interoperability and the integration. Provided the mutually interdependency of either factors, the successful actualization of connectivity is esteemed as delicate undertaking. Initially, the thematic area of interoperability is scrutinized.

Ide and Pustejovsky emphasize the fact that "*Interoperability* is measure of the degree to which diverse systems, organizations, and/or individuals are able to work together to achieve a common goal" [55]. In connection with Industry 4.0, the procedures associated with the interoperability will bring specific software elements, procedures, solution approaches as well as mutations of the industrial environment to light [56]. To ensure the diagnostic analysis of ensuing concerns, an architecture consisting of four levels has been established. Essentially, the operational, systematical, technical, and semantic interoperability compile the structure [57]. The operational or organizational interoperability attaches importance to the structure of languages, standards and interdependency between Industry 4.0 and CPS, whereas the applicable interoperability focuses the attention on the determination of directives methods, model and standards. By considering the above positioned technical level of interoperability, a step forward has been token by means of the determination of directives methods, model and standards. Conclusively, the final level of the architecture can be illustrated. The so-called semantic interoperability acts as a sort of guarantor for the data or information exchange between human or machines. The explication of the architecture model constitutes the essential prerequisite for the introduction of the operability framework.

According to Lu, three frameworks can be distinguished, namely "Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR); Interoperable Delivery of European eGovernment Services to public Administrations, Business and Citizens (IDABC); and Advanced Technologies for Interoperability of Heterogeneous Enterprise Networks and their Applications (ATHENA)" [58]. Going back to the year 1996, the American Defense Department contrived the first frame of reference. C4ISR concentrates on three interoperability levels, namely the operational, systematic, and technical one. The intention to cover the provision of a sufficiently high grade of interoperability among the architecture, results in the overcome of multi-national boundaries [59].

Shortly thereafter, the European commission reacted by means of the European Interoperability Framework (EIF) and brought the IDABC program into living. In comparison with the previously presented framework, the IDABC does not take the systematic, but the semantic interoperability level, into account. Concretely, this signifies that EIF stresses more the aspects belonging to the information exchange among human and machines [60]. In conclusion, the ATHENA project is introduced. The confluence of several disciplines, which entails enterprise modeling, architectures and platforms, as well as ontology, enabled the emergence of one of the most relevant interoperability frameworks. Based on a holistic approach, ATHENA handles interoperability, heterogeneity and complexity in order to satisfy user requirements of the entire industrial realm [61].

To put it briefly, interoperability can be equated with "coexistence, autonomy and federated environment" [62]. Although *Integration* is strictly related to connectivity, it embodies distinct concepts like coordination, coherence and uniformization [62]. The ISO 19439:2006 defines the enterprise integration as "a process of ensuring the interaction between enterprise entities necessary to achieve enterprise domain objectives" [63]. Vernadat provides in his research work "Enterprise modeling and integration (EMI): Current status and research perspective" an exhaustive classification of the typologies of integration, which comprises the horizontal, vertical, intra-enterprise and inter-enterprise integration [64].

By virtue of the Industry 4.0 pioneering research work accomplished by the Deutsche Akademie der Technikwissenschaften (ACATECH), only three typologies, namely the horizontal, end-to-end and vertical integration, are considered [65]. While the horizontal and vertical one is affiliated to the manufacturing system, the end-to-end is strongly connected to engineering. The vertical integration allows the establishment of a relation between IT systems operating at diverse hierarchical stages over the course of the manufacturing process. Precisely at this point CPS assume an essential mediating function, which enhances the factory planning quality by means of flexible and reconfigurable manufacturing systems [66]. An essential prerequisite for exploiting the resulting potential, is provided by the horizontal integration. In this case, the attention is put on the information exchange including all passages within the business planning processes and manufacturing. Finally, the slightly different end-to-end integration is treated. The mentioned discrepancy compared to the previously typologies consists in the fact that end-to-end integration incorporates the whole value chain, starting from the product engineering passing through the manufacturing and ending with the customer [65]. The primary objective is constituted by the closing of existing gaps throughout the chain [65].

2.3.5 Automation: industrial robots and human-machine interaction

The lively history of automation reflects undoubtedly the wishful thinking of human beings. Although, futuristic aspects associated with automation have become firmly rooted in the minds of most people, the historical beginning lies far back in the past. In the ancient Greece mythologies dealing with artificial entities were narrated, whereas in more recent times film directors used to supplant them through feature movies [67]. The same applies to physical inventions, which prepared the ground for the birth of automation and robotics. Once again, the ancient Greeks, assumed a pioneering role through the creation of the so-called clepsydra or water clock, whose function consists in the time tracking [68]. Further evolutionary steps were undertaken over the course of the first industrial revolution, in which the mechanization of production processes was of interest. One of the most famous inventions is the “spinning jenny”.

However, the mentioned inventions do not pertain to the automation realm, even if their contribution to the emergence of robotics and automation was essential. In fact, up to the year 1920, in which Karel Capek presented the drama “Rossum’s Universal Robots”, the expression “robot” was not even existing [69]. The author derived it from the Czech expression “robota”, which stands for servant. Briefly after coining the term, the real development initiated. Crucial was the strong industrial position of America by dint of the second industrial revolution. Precisely in this portion of the global history, the expression automation was shaped by Henry Ford. For the industry titan, “automation is a process in which a machine transferred a sub-assembly item from one station to another and the positioned the item precisely for additional assembly operations” [70].

The existing favorable framework conditions enabled the confluence of the figment of the imagination propagated by science fiction and the real material world pertaining to the technological realm. The vision and stubbornness of two inventors, namely Joseph Engelberger and George Devol, brought the first universal automated or “unimated” device into being. The peculiarity of the universal automation consisted in the fact that the developed entity was able to execute a large variety of diverse operation, which ensured a wide-spread applicability area. One year after the patent registration of the “Unimate” that occurred in the year 1961, numerous industrial companies acquired the new invention with the purpose of enhancing the productivity [71]. The successful establishment of robots lead to the creation of a new science called robotics, which is characterized by the harmonization of distinct areas such as electrical engineering, mechanical engineering as well as computer science. According to the Robotic Industries Association (RIA), a "robot is a programmable, mechanical device used in place of a person to perform dangerous or repetitive tasks with a high degree of accuracy" [72]. Provided the principle of universality related to robots, it is notable to mention that attention will be put on industrial robots, which are specified as "automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications" [73]. Several types of classification are at disposal. Anyway, the one belonging to the mechanical structure is the most utilized. The five classes are represented by Cartesian robots, SCARA robots, parallel robots, cylindrical robots and articulated robots. The simplest mechanical structure is represented by the "Cartesian robot, whose arm has three prismatic joints and whose axes are coincident with a Cartesian coordinate system" [74].

The field of application typically comprises the manipulation of heavy and large objects. The Selective Compliance Assembly Robot Arm or SCARA possesses two rotary joints that allow to perform ideally vertical assembly tasks. The third classification focuses on parallel robots, whose concurrent prismatic or rotary joints are exploited to perform pick and place application. Thanks to the achievement of sustained operating velocity, this sort of robot became popular also in the simulation realm. The cylindrical robot, which is composed of one revolute and two prismatic joint, is implemented in industrial environments for the accomplishment of assembly tasks. Finally, the articulated robots, which are characterized by the presence of three rotary joints is introduced. The versatility that distinguishes this category of robots can be considered as the root cause for its wide-ranging distribution [74].

The robotic realm was revolutionized in the year 2009, when collaborative robots or so-called CoBots were launched on the market [75]. By contrast with the traditional robot-conception, in which the autonomous task accomplishment is considered as absolute priority, CoBots physically interoperate with humans by co-utilizing one single working area. The success of the mentioned collaborative application mainly depends on the integration of intelligence in robotic systems. Even if robots have dominated the robotic realm for decades, several associated components, such as gripper, begin to move into the spotlight. The so-called Co-Act Gripper JL1 of Schunk, named after the famous German goalkeeper and Schunk brand ambassador Jens Lehmann, was presented last year at the Munich trade "Automatica" [76]. The peculiarity of the innovative gripper consists in the ability of collaborating and interacting by means of advances sensor technologies with humans. The newest trend explicitly demonstrates the relevance of the human role within the industrial environment, which led to put enhanced attention to the subject of human-machine interaction.

The mutual influence between the parties is accomplished by means of a human-machine systems (HMS) that entail humans, machines and the connective link termed as human-machine interface [77]. The first two components have to be interpreted broadly, as they encompass a great variety of human users and machine profiles. However, the attention is put on their linkage. The Human-Machine Interface (HMI) is subdivided into components, which are represented by the presentation and control, dialogue and data preprocessing, the application interface, user model, explanation and tutoring and finally the application model. While the last mentioned are considered as standard interacting features, the presentation and control as well as the dialogue and data preprocessing are of particular importance. The dialogue and data processing deal with the information flow. The aim of this component is to illustrate the correct information in the adequate time frame in order to maximize its utility for the respective human user. However, the substantial interaction occurs by the use of the presentation and control unit. The present technological competence enables the employment of variegated control possibilities that can be exerted applying several forms such as the direct, bio-signals and conclusively the control devices. Actually, the last form is the predominant one in the machining realm, due to the fact that it enables the user to control efficiently and intuitively the operating device [78].

2.3.6 Additive manufacturing: Individual Production on Demand

Additive Manufacturing (AM) forms the sixth pillar on which Industry 4.0 is based on. The technology allows responding to the individualization requirement by enhancing flexibility and adaptability of the technology regarding to product variety and volume. AM, even termed three-dimensional (3D) printing, was specified by the American Society for Testing and Materials (ASTM) as "the process of joining materials to make objects from 3D-model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [79].

The technology has already been developed in the mid-1980s with the objective to fabricate conceptual or functional prototypes to minimize the development phase, as well as the time to market of new products [80].The mentioned application typology, also well known as rapid prototyping (RP), is one of the most appreciated and widely implemented by companies operating in diverse sectors. The extraordinary application outcome leveraged the technological diffusion, which resulted in the formation of Rapid Manufacturing (RM). It is specified by Hague et al. [81] as "the production of end-use parts from additive manufacturing systems". Uninterrupted amelioration of AM-technologies supported the enlargement of the application realm with the introduction of Rapid Tooling (RT), whose focus lies on the generation of proper manufacturing tools. RT can be categorized into direct tooling, which has the objective of providing tools for industrial use, and indirect tooling that forms preproduction models of tools [82]. The mentioned application typologies can be considered as a first categorization of AM that is followed by the classification based on material types.

AM-machines utilize four different materials, including polymers, metals, composites and ceramics. The polymeric material and in particular polyamide is one of the most attractive due to its mechanical properties and costs. RP-machines are typically supplied with polyamide, whose quality depends on the use of the physical prototype, while RT creates tooling equipment made out of polymeric or metallic material. The application, which exploits all four types, is RM [80].

The material can be supplied in three forms, including powder, liquid or solid. Powder, which can be composed of different material types, offers a wide range of compatible technologies including Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Direct Metal Deposition (DMD), Selective Laser Melting (SLM) and Three-Dimensional Printing (3DP). The supply of liquid, which consists of polymeric material, occurs for technologies like Fused Ink Jet Printing (IJP), Stereo-Lithography (SL) and Deposition Modelling (FDM). The only AM-process that can operate with all four material types in a solid form is the Laminated Object Manufacturing (LOM) [83].

Even if enterprises in most instances adopt AM-technologies to create prototypes, other applications, like RM and RT supported by material-quality and technological advances, become attractive for certain industrial sectors, which focus on the successful launch of an Industry 4.0 conform fabrication process. While the automotive, aerospace and medical industries are considered the prime examples of AM-technologies implementation and development, future advances in the new industrialization area promise a vaster diffusion of AM-technologies. Indeed, several academic institutions such as the Massachusetts Institute of

Technology (MIT), endeavor to solve technological problems associated to process speed and quality. The novel AM-technology termed as “Fast FFF 3D printing” allows to generate highly qualitative components in a tenth of the time [84].

To conclude the AM-procedure, which is based on an eight steps sequence is presented [85]: The first step consists of the conceptualization of the part by means of the Computer-Aided Design (CAD) software. It is important to convert the generated file into a STereo-Lithographic (STL) document, which is transferred and manipulated according to machine requirements. After the adjustment of the STL-file, the AM-equipment is regulated to obtain the optimal setup. The production process can now be launched. Depending on the utilized material quality and the elaboration accuracy of the machine, the produced object has to be cleaned and processed by other machines. The last step is composed of the application of the created 3D-object.

2.3.7 Digitalization: Simulation, Virtual Reality, Augmented Reality, Digital Factory, Digital Shadow and Digital Twin

The unstoppable pace of digitalization promotes the confluence of real and virtual sphere by scrambling their already porous borders. At the early stage of the propagation of the phenomenon, it became clear that the impact on a wide variety of realms will be substantial. Peculiarly from an Industry 4.0 perspective, the increasing and progressing digitalization assumes a pivotal role. As a matter of principle, it forms a portion of the backbone on which the fourth industrial revolution is grounded. Gartner Inc., which is considered as a worldwide leading research and consultancy company, provides a definition of business-related digitalization [86]. Correspondingly, digitalization is referred to as “the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business” [86]. The submitted definition reveals the comprehensive nature of the phenomenon, which will not be covered entirely within the sub-chapter. Indeed, in the context of this work several priorities are set, so that Simulation, Virtual Reality, Augmented Reality, Digital Factory, Digital Shadow and Digital Twin will be presented. Figure 5 presents a graphical summary.

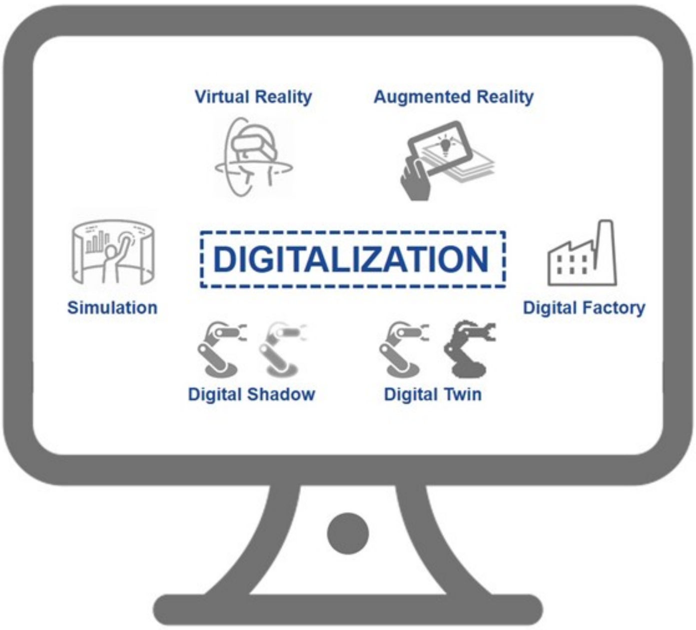

Figure 5: Digitalization in Industry 4.0.

Simulation is unambiguously the concept that is commonly most known. The reason for this lies in its enormous spectrum of application that comprises manifold disciplines. "Simulation modelling and analysis is the process of creating and experimenting with a computerized mathematical model of a physical system" [87]. ISO brought Simulation Interoperability Standards Organization (SISO) into being in order to support institution, above all the US Department of Defense, in dealing with complex and expensive problems. In fact, the main purposes of simulation can be recapitulated as analysis, research and development, test and evaluation as well as training [88]. The advantages of exploiting simulation do not exclusively concern monetary aspects. In numerous instances the experiment possesses a hazardous profile, which does not allow the "real" conduction. Despite this fact, the time factor enhances the popularity of simulation. Concretely, simulation offers the possibility to speed up experiments and to handle leaps in time. The last main benefit is associated with the alteration of models, in which additional elements and the corresponding consequences can be enclosed and evaluated. One the other hand some negative aspects concerning costs, labor-intensity, time exposure as well as data interface problems discourage enterprises from employing simulation. However, at present due to the massive technological progress the advantages related to simulation undeniably outweigh the disadvantages. The application field characterized by a lofty degree of compatibility is represented by the factory planning. The beginnings reach back in the year 1960, in which the primal computer networks were utilized to shape the form of factory related plans.

Passing through the implementation period of two dimensional and three-dimensional CAD, primordial *Virtual Reality (VR)* systems were implemented in the 1990s. According to the Virtual Reality Society (VRS) VR is "the term used to describe a three-dimensional, computer generated environment which can be explored and interacted with by a person. That person becomes part of this virtual world or is immersed within this environment and whilst there, is able to manipulate objects or perform a series of actions" [89]. The inclusion or immersion of the user, which is contemplated as the key concept linked to VR, can be ensured through the implementation of headsets, monitors, workbenches, walls or caves.

While VR focus on the digital reproduction of the real environment, *Augmented Reality (AR)* aims at supplying the enhanced version of reality in real time. In order to take full advantages of AR, a combination of semitransparent lenses and wearable computer is formed [90]. Considering the properties of the two presented technologies, it can be stated that VR comes into play within the product development- and industrialization phase, whereas AR is excellently suitable in the operation or maintenance of the fabrication system [91].

Following the digitalization timeline associated within the factory planning, the *Digital Factory (DF)* has been conceived as notable in the 2010s. The novelty consists in the merge of several digital tools and methodologies in the production engineering real. The Fraunhofer institute defines DF as "a comprehensive network of digital models, methods, and tools, including modelling, simulation and 3D/Virtual Reality visualization, integrated by a continuous data management" [92]. In comparison with previously regarded digital advances, the DF facilitates a conception of an optimized production site already in the planning phase. In conclusion, the newest trends, namely the *Digital Twin* and the *Digital Shadow*, are illustrated. The digital shadow entails the exteriorly generated data profile belonging to a component or a product. The last named are created by means of algorithms that contain the acquisition, analysis, evaluation and consolidation of data. The objective of the digital shadow is to supply a basis for the decisions making process [93]. Although, the intents of the digital twin and shadows are similar, a conceptual distinction has to be emphasized. Firstly the definition is presented. The digital twin is “a comprehensive physical and functional representation of a component or product, which includes all necessary information for its processing in all life cycle phases” [94]. To recapitulate, either follow the objective of furnishing additional information. The digital shadow offers exterior information, whereas the digital twin focuses the attention lifecycle related information.

2.3.8 Safety and Security: Dangers of the Cyber Physical World

The revolutionary alterations induced within the fourth industrial revolution unavoidably expose enterprises to significant risks [95]. In order to guarantee the integrity of entities affected by Industry 4.0, first among the concerns an accurate distinction between safety and security, which are of course sharply affiliated terms, has to be drawn. The discrepancy between the two concepts, which is stemmed from the adopted point of view, is relatively plain to comprehend. Safety puts emphasis on the protection of the environment from an entity, whereas security aims at preserving an entity from the environment. Conventionally, *Security* is determined as “the state of being free from danger or threat” [96]. On the contrary, *Safety* is specified as “the condition of being protected from or unlikely to cause danger, risk, or injury” [97]. Although the definition might appear confusing at a first sight, the essence of the disparity can be explicitly illustrated through an example. Users or more generally people should not be endangered by smart products or CPS, which could be interpreted in a broader sense as Industry 4.0 affiliated entities, but also data or information belonging to those entities should not be wrongly utilized. The clarification is implicitly linked to the fact that safety deals prevalently with the technological sphere and, controversially, security is closer to the digital or ICT realm.

The third industrial revolution marks the beginning of the safety and security regulation progression [17]. Provided the recentness of ICT, most safety provision are more matured in respect to security regulations or standards [98]. The disparity in maturity, which is perceived as the major issue within the new industrial revolution, generates the need for massive improvements related to the cyber physical security realm. In other worlds, this signifies that enterprises are forced to map out and implement a new Industry 4.0 protection strategy. According to ACATECH, two aspects assume a pivotal role within the fourth industrialization of an enterprise. On the one hand, the security as a result of design is put into the limelight and on the other hand approved cyber security strategies, architectures and standards should achieve more attention [65]. The initial principle requires a radical rethinking, in the sense that security is not provided as a supplement after the conception phase is completed, but it is an integral part of it. This implies that protection is involved from scratch. Subsequently, the creation of security strategies, architectures and standards is taken into consideration. Essential pre-requisite for the realization are the establishment of communities or organizations, whose fundamental function comprise the generation of standardized solution approaches for Industry 4.0 related issues. Even though the ISO/IEC 27032:2012 norm, which was published in the year 2012, serves as first guideline for cybersecurity, a great deal of work has to be accomplished [99]. The rapid advances in the IT-sector are the reason for the redundancy of the supplied compendium of cyber security techniques. However, ISO in collaboration with IEC is laboring to review the mentioned norm. On this occasion, the complexity associated to novel industrial system, which derives from their networked nature and autonomy, will be taken into consideration. Be that as it may, the generation of such unified solution concepts is conceived as a delicate endeavor. According to what stated, it can be deduced that the Industry 4.0 protection strategy predominantly keeps security issues on the foreground, but without neglecting the intensive involvement of safety aspects. Rephrased: a dual and universal approach is claimed to manage contemporarily security and safety due to their mutually interdependency [100]. The influence of security measures on safety aspect as well as the opposite condition should be examined carefully before starting their implementation. In order to successfully put the strategy into action, safety or security measures should be characterized by user-friendliness. It is a matter of common knowledge that regulations are considered as annoying, which is the root cause according to which users try to bypass them. The illustrated behavior pattern results in disastrous repercussions. The problem could be partially solved by setting up regulations that are able to guarantee protection and at the same time satisfy to user requirements. In addition, an intuitive interface can act as facilitator [65].

2.3.9 Smart Products: Monitoring and Autonomous Control

The peculiarity of Industry 4.0 is fundamentally characterized by the enhancement of industry with cutting-edge digital technologies [101]. The extension of the mentioned founding principle within the industrial environment is perceived as the trigger for its transformation. In fact, the intensive involvement of internet technologies lends a distinctive character to objects, in which smartness is embedded. The concept encompasses diverse industrial areas and objects [102]. Since within the section dedicated to the Industry 4.0 fundamentals, the emphasis has been placed majorly on manufacturing or digital systems, aspects related to products and in particular Smart Products are extensively discussed to ensure completeness. Provided the versatile nature of Smart Products, it is impossible to individuate a standardized definition. However, several researchers attempt to provide extensive specifications.

Mühlhauser, for example, contemplates Smart Product as “an entity (tangible object, software, or service) designed and made for self-organized embedding into different (smart) environments in the course of its lifecycle, providing improved simplicity and openness through improved product-to-product and product-to-user interaction by means of context-awareness, semantic self-description, proactive behavior, multimodal natural interfaces, artificial intelligence planning, and machine learning” [103]. Conversely, Gutiérrez et al. consider the dispersion of the term as insurmountable obstacle for the clarification of the concepts [104]. Within their research work “Providing a Consensus Definition for the Term Smart Product”, they dissociate from the traditional term by introducing a new and more general one, namely “Smart Things”. Albeit the terminology assumes an essential role, it is preferable to concentrate on the attributes of smart products. Porter and Heppelmann offer an overview of capabilities possessed by smart products [105], which is presented by means of figure 6.

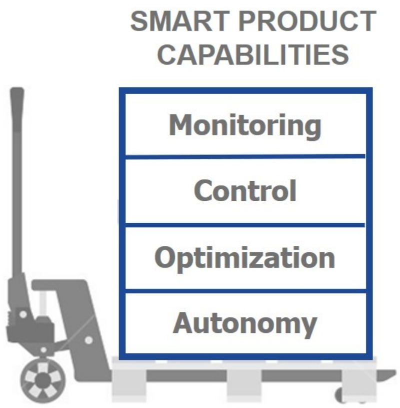

Figure 6: The capabilities of smart products (adapted from [105]).

The first is represented by monitoring. Concretely this entails that products are able to supervise themselves and their surrounding area. Big Data is the term of the consequence of the adoptability of the named feature. The monitoring goes hand in hand with the control. In other words, it can be considered as a precondition for the effective introduction of its governance. The advanced state of technology allows the user to adjust the settings of a product remotely and in real-time. It is almost superfluous to mention that the controlling enables the maximization of the user utility. Exercising sole control is not sufficient. One of the most relevant attributes consists of the self-optimization.

Specifically designed analytical procedures and algorithms are capable of providing almost perfect performance, which could have been achieved by means of continuous self-improvement. The last capability, which divides the user-community into two parties, is undoubtedly the autonomy [106]. Originating from the successful inclusion of all the previously listed capabilities, it includes mainly the self-operation and diagnosis. Straightforwardly, the four illustrated capabilities act as enabler in the amelioration of profitability and continuous growth [107].

With the aid of data deriving from the upgraded user-involvement, enterprises are able to position products more accurately on the reference market. In addition, superficial features associated with products can be eliminated after the recognition of their disuse. The complicated nature of smart products increases the barriers for possible new entries in favor of established companies. On the contrary, start-up companies would have to overcome much greater difficulties.

The principle reason pertains to exaggerated high fixed costs. Irrespective of opportunities and threats for all kinds of enterprises, smart products will affect under any circumstances all value chains, from the research and development department to the aftersales. The monitoring nature of smart products allows obtaining to-date fresh data, which have to be traduced in meaningful information [65]. The last-named forms the base for the new product development phase, whose time span is shortened perpetually. Marketing is one of the company function that benefits the most from the data collected by smart products. In the past, major concerns related to lack of data exists for this type of department. A similar dynamic can also be noticed in the aftersales, whose service quality can be massively improved.

2.3.10 Work 4.0: redesign of future work

Industry 4.0 clearly brings technological and digital innovations into focus. Having a closer look at the industrial developments, the predominance of technology immediately catches the eye. Steam, electricity and digitalization constitute only few examples. However, an accurate examination of the historical developments demonstrates also that the human party represented by the workforce, assumes an essential role in the industrial evolution [108]. Indeed, the real driving force behind the revolutionary success are humans that enabled the implementation of the innovation.

In the past little attention was paid to workers, in the sense that changes affecting the work dynamic were always perceived as an effect of innovation. The industrial environment endorsed the passive human role, instead of putting proactive measures into action. In the fourth industrial revolution this error should not be repeated. A prerequisite for the success of Industry 4.0 is the harmonization of “technological, digital and human resources” [109]. Admittedly, first of all the ascertainment of the seamless coexistence has to be scrutinized. No doubt that the working landscape will undergo profound changes, but how will it affect the role and profile of workers?

The increased degree of complexity arising from the networked structure mainly forces humans to adequate and ameliorate their system management and problem-solving capabilities. The great autonomy attached to systems within an Industry 4.0 environment, undeniably prioritize the human in the role of the decision-maker [110]. In addition, not only hard skills but even soft skills such as communication and time management require an upgrading. Although the possibility to improve sounds very attractive and easy to apply, some dark sides surface. Considering the emerging challenging commissions provoked by the implementation of innovation, the workforce runs into danger of not being able to keep the pace. The result is frustration and alienation. In particular, the work category, whose center of gravity lies on the manual labor, suffers the most from the innovation. The reason behind this fact, consists in the steady decline of the manual work within the industrialized environment [111].

In order to deal with the emerging challenges, the most suitable approach to adopt seems to comprise a socio-technical perspective. This implies that work organization, professional education and technology should go hand in hand with the objective of supplying a unique answer to the "Work 4.0" question. To achieve the goal, the scientific management designed by Taylor is scrutinized [65].

Particularly in the early stage of the industrial revolution the implementation of the methodology proposed by Taylor could be of substantial benefit for enterprises. In other worlds, the determination of labor procedures belonging to Industry 4.0 manufacturing is perceived as a mandatory requirement for guarantying efficiency and productivity. In light of this, the ACATECH supports the initiative "better, not cheaper" [65]. Besides the monetary considerations associated to the workforce, enhanced emphasis should be put on qualitative aspects. In order to preserve the expertise of workforces, focused trainings and a continuous professional development should become a norm within working environments. Provided the digitalization trend in industry, ICT-skills move in the spotlight. Concretely, specific designed trainings, which deal predominantly with digital aspects, should accompany professionals during their entire evolutionary path.

Apart from expertise, the networked nature of organization claims for the creation of bridges between various departments, which implies the successful application of social skills [112]. The main goal is represented by the establishment and preservation of the enterprise cohesion. In summary, the fourth industrial revolution affects the profile of professionals that are in need of enhancing hard and soft skills. In addition, to keep the pace provoked by the digitalization a continuous development should become an integrated part of the common working philosophy.

2.4 Strengths, weaknesses, opportunities and threats of Industry 4.0

In this juncture the culmination of the enthusiastic wave for the new industrial revolution has been reached [113]. The enduring Industry 4.0 fascination engenders the predominant consideration of strong points. Although, positive aspects take the center stage, some research works already have highlighted vulnerabilities of Industry 4.0, which could jeopardize the stability within enterprises [114].

Apart from the nature of the revolutionary aspects with respect to which researchers and experts have not found a consistent point of reference, in the matter of impact all are on the same page. The industrial revolution will profoundly amend the global industrial landscape, provoking opportunities and simultaneously menaces for all kind of enterprises [115]. Any revolution, independently of its nature, has to be characterized by a substantial replacement, whose purpose clearly lies in the enhancement. In other words, the presence of strong points is considered as essential prerequisite for the initiation of such a radical process. The fourth industrial revolution affects the entire structure of a company and gives importance to the network in which the single industrial entities are embedded. Especially the interconnectedness complicates considerably the management of an industrial system and the achievement of performance objectives [108]. Indeed, the uppermost and immovable maxim within the industrial environment comprises the exploitation of increasable productivity. Any enterprise has the aim to make the highest utilization of in-house resources. The mentioned principle is strictly related with the objective of the new industrial wave, which consists in the development of the business performance to the maximum.

At present the entire industrial community perceives Industry 4.0 as movement, which is characterized by strengths that outweigh shadow sides [116]. In this regard, the entrenched common view and the corresponding widespread volition to put Industry 4.0 into practice is definitely a favorable departure point for the concept realization. The fundamental requirement for the goal achievement is represented by the existence of technological and digital innovations that comprise CPS, IoT, Automation and Digitalization. In order to take advantage from the named novelties, a symbiosis between them has to be formed, which is definitely not an ordinary concern. Substantial monetary funds have to be raised in order to acquire the novel means, which subsequently have to be related through functional cross-links [3]. The connectivity of new technologies is a major topic of debate within the Industry 4.0 research communities. The broad utilization range, which comprises the complete industrial landscape, complicates the establishment of a universal-functioning connectivity solution. In addition, the interests of the involved industrial actors significantly diverge, so that a concerted approach is not in prospect yet. Numerous institutions are aware of the deficiency and have already brought to life standardization bodies, whose mission consists in the determination of approved uniformity. Several successes have been recorded, especially in the realm belonging to CPS with the 5C-Architecture [19]. Anyway, the realization of a comprehensive standardization-solution related to Industry 4.0 is still far from complete. Although the unification is surely perceived as a challenging issue, the greatest concern is represented by safety and security.

Dangers concealed within the cyber-physical world act as a deterrent that is responsible for the procrastination of the implementation start [98]. Hence, on the one hand Industry 4.0 should not endanger users, which day by day utilize information-rich products, and on the other hand enterprises should not be harmed though the misuse of data. According to the previously listed threats, it becomes clear that the wave triggered by the fourth industrial revolution undoubtedly emphasizes technological aspects. In this sense, the acute danger posed by not taking the human role seriously into account is underestimated. Even if it does not seem apparent, the workforce constitutes the key factor, which determines the success of the Industry 4.0 realization. Therefore, close attention is devoted to the work organization and design as well as to the individual professional figures that are in need of tailored trainings and a continuous occupational development.

The last aspect, which is responsible for the diffusion of insecurity within the industrial environment, is connected to law and legislation. A favorable regulatory framework should be established in order to overcome successfully the introductory phase. Admittedly, the jeopardies associated with the Industry 4.0 realization in this light could assume intimidating effect, it has to be stated that the opportunities, which could be seized, are sizable. Even if it might appear fairly straightforward, the satisfaction of customer requirements is ranked as the primal opportunity that provides a tremendous potential [65]. By means of the technological advances that affect entire supply chains, enterprises are able to accommodate tailored client requests. Particularly, the manufacturing of single batch-sizes, which is enabled through the application of AM-technologies, allows to reach a so far not achievable degree of customization. In addition, short-termed modification can be considered provided the responsiveness provided by digital technologies.

The excellent maneuverability is not merely availed to bespoke products, but also to increase the performance in terms of flexibility within the companies. Concretely, CPS and networked entities should enhance the dynamism of enterprises due to rapid adjustable setting system, which comprise essential industrial features such as time, quality, sustainability as well as costs [32]. Time, which was first mentioned, has not accidentally acquired the primal position. In particular, the required time to accomplish the decision-making process, asks for a shortening. Industry 4.0 technologies, which focus on real-time data or information exchange, allow to achieve the mentioned target, even if the networked scenario in which enterprises are embedded, tends to complicate the selection procedure at every enterprise level [110]. Needles to mention that entrepreneurial decisions influence the productive performance.

However, industrial innovations facilitate the maximization of resources efficiency. Evidently, every enterprise pursues the objective of obtaining the hugest possible output by implementing the lowest possible input. Within the fourth industrial revolution, the advanced governance mechanism enables precise setting adjustment, whose effects are reflected in form of reduced resource consumption. The clearest example can be observed in the reduction of emissions. Production sites are definitely not the only entities that benefit from the changes. The flexibility affects also the human workforce, whose work-life balance quality can be enhanced. The smart work organization and design provides the possibility to form plans, which meets preferences of professionals. The last point belonging to the human sphere, is represented by the emergence of unparalleled career opportunities. In particular, the IT- and engineering realm will experience a positive upswing [111]. Figure 7 summarizes all the mentioned strengths, weaknesses, opportunities and threats of Industry 4.0.

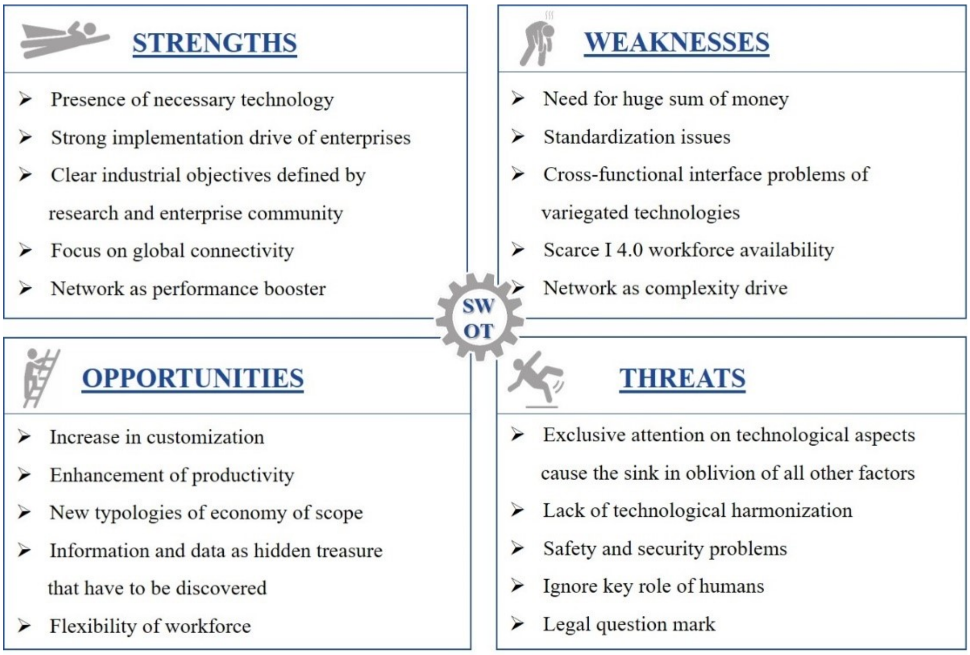

Figure 7: The SWOT-analysis of the fourth industrial revolution.

2.5 Overview of existing assessment models and maturity stages models

The conclusive section of the state of the art, which is devoted to the illustration of the existing assessment models and maturity stage models, should enable a smooth transition to the subsequent block of the master thesis. In order to guarantee the realization of a new assessment tool for Industry 4.0, the nature and the related characteristics of successfully employed tools is taken into consideration. First of all, the specifications of the literature research centered on assessment or maturity stage models is detailed. Subsequently, to supply a complete analysis respectively two assessment models and two maturity stage models come into question.

2.5.1 Structure of Assessment and Maturity Stages Models

The assessment procedure as well as the determination of maturity stages enjoy popularity in the most diverse branches. Even though countless examples could be cited, in the next sub-sections it is beneficial to put the focus again on industrial subject matters by means of the presentation of two prime examples on the one hand for assessment models (section 2.5.2) and on the other hand for maturity stage models (section 2.5.3.). In order to establish the mentioned models a brief research exploiting functionalities of the scientific database Scopus was executed. By means of the research query ((TITLE-ABS-KEY ("maturity model") OR TITLE-ABS-KEY ("assessment")) AND TITLE-ABS-KEY ("industry 4.0")), an output of 61 search hits was obtained. Figure 8 shows the system of the performed literature review as well as the obtained results.

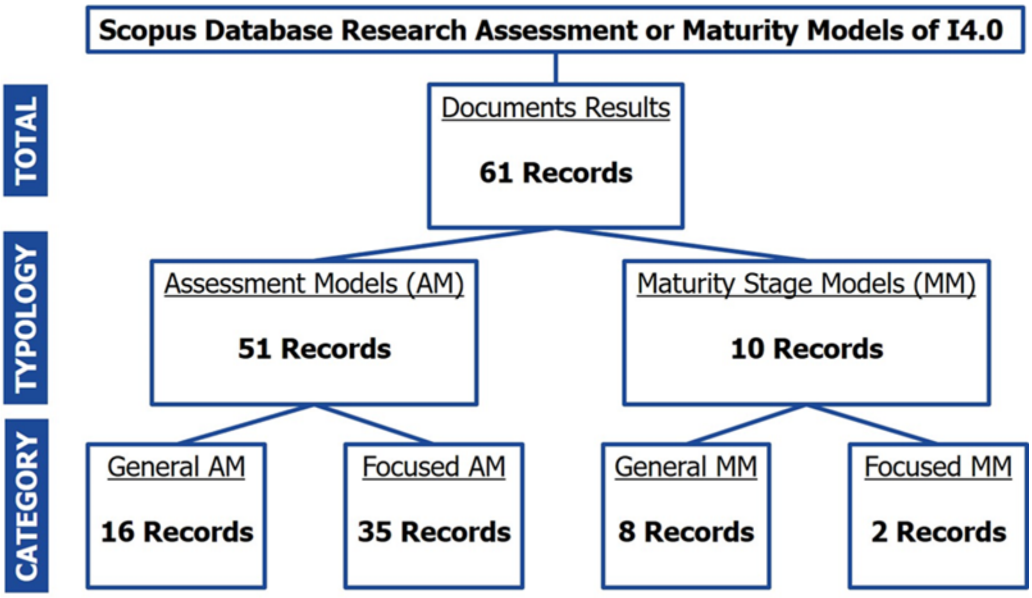

Figure 8: System and quantitative output of the review related to assessment and maturity models.

The execution of an accurate qualitative analysis as a first passage enables the establishment of the quantity of records related to the typology of model, which is epitomized by either assessment models or maturity stage models. For each typology of model two categories are established. The mentioned categories are on the on hand represented by “general”, in case the model does not exhibit a particular focal point, and on the other hand by “focused”, in case the model is concerned with a peculiar industrial thematic area. To put it succinctly, models providing an evaluation of an entire industrial entity fall into the first category, whereas models that declare to concentrate on a sub-area, such as the manufacturing system, are associated with the “focused”-category.

2.5.2 Existing Assessment Models of Industry 4.0

As announced in the introduction text two assessment models of Industry 4.0 are presented. Although assessment models focusing on the fourth industrial revolution are still in their infancy, the increasing popularity among the industrial research community is perceptible. Simply by looking at the output composed of 61 search hits established by exploitation the Scopus database potential, the recent publication years catch the eyes. The qualitative literature review allowed to identify two representative samples that are respectively portrayed by "Development of an assessment model for Industry 4.0: Industry 4.0-MM" and "Multi-Criteria Evaluation of Manufacturing Systems 4.0 under Uncertainty". Besides the different compositions of the two-research works, even the considered perspective is not identical, in the sense that the first listed model follows the objective to encompass Industry 4.0 in its entirety, whereas the second one focuses specifically on the manufacturing system realm.

The scattered nature of "Development of an assessment model for Industry 4.0: Industry 4.0-MM" can be immediately recognized in the introductory stage [117]. The authors point out general conditions of the German economy, which unambiguously is perceived as the motive power behind the fourth industrial revolution.

The realization of a common knowledge base is immediately followed by a systematic literature research; whose aim consists of the generation of a maturity models database. Seven frameworks and their related characteristics, which are classified into model name, research context, maturity levels and finally dimensions, are presented in tabular form. The ranking of the already implementable models is grounded in six assessment criterions, which are represented by "fitness for purpose, completeness of aspects, granularity of dimensions, definition of measurement attributes, description of assessment method as well objectivity of assessment method" [117]. To provide a complete review, the evaluations are clarified and reinforced through brief statements. The conclusion of the extensive review process allows to pass over to the actual development of an Industry 4.0 assessment model. In order to be on the safe side, the authors opt for the ISO/IEC 15504 - also termed as "Software Process Improvement and Capability determination (SPICE)" as base for structuring the maturity model [117]. In this light, the framework relies on two separate dimensions, which are respectively the capability, which in a broader sense entails the evolution stages, and the aspect dimension, which is an inseparable bundle composed of infrastructure, information systems, data organization and integration. Even though almost all key terms offer a clear-cut idea of the significance, each is detailed with the support of a brief statement.

The aspect-dimension is characterized by the inclusion of "asset management, data governance, application management, process transformation as well as the organizational alignment" [117]. The asset management implies the administration of enterprise infrastructure, whose main components entail IT- and manufacturing systems. The data governance, which assumes a vital role within the novel industrial movement, describes all the features around the subject matter data and information. The key term "application management" that at a first sight seems to be not self-evident, focuses on the harmonization of the assets belonging to the enterprise. Uppermost objective is constituted by the maximization of the industrial efficiency. In contrast, the organizational alignment puts the attention on the generation of a technological and organizational balance. To conclude the process transformation is illustrated. Intrinsically, it deals with the alteration of company processes such as planning or production provoked by the introduction of Industry 4.0 innovations. The exhaustive explanation of the aspect dimension helps to tackle the topic centered on the capability dimension. As stated previously six gradations are considered by authors. Provided the fact that the key terms associated to the levels do not ensure the full comprehension, concrete examples are showcased. Commencing with the undermost stage, the so-called incompleteness, it can be mentioned that every requisite for the implementation of Industry 4.0 measures is absent.

The first proper level, named performance, symbolizes the willingness of the enterprise to transit to an Industry 4.0-conform entity. Genuine digital or manufacturing technologies such as CPS or IoT can be found in the introductory phase. The performance stage is followed by the management level, which according to the authors is linked with the digitalization of the company. Operations go hand in hand with predefined data sets and physical items are epitomized also in the virtual word by means of digital twins. The digitalization acts as predecessor of the establishment. In practice, the vertical integration throughout the enterprise as well as the standardization are successfully employed. Climbing up the hierarchy ladder, the predictability, which relies on horizontal integration and control, arises. The uppermost floor of the dimension is occupied by the optimization stage. Consisting of integration towards product life-cycle, innovation and self-optimization, it is definitely the most severe level to reach. By means of the first performed analysis it stands to reason that the assessment model aims to provide first aid to company in the Industry 4.0 movement. Figure 9 summarizes graphically the presented assessment model.

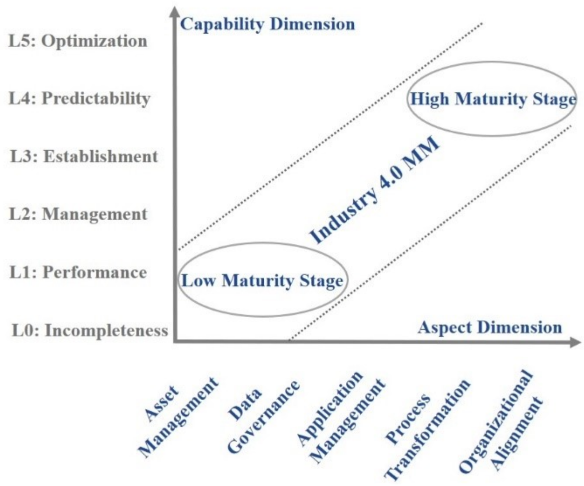

Figure 9: Structure of the first assessment model (adapted from [117]).

The research work "Multi-Criteria Evaluation of Manufacturing Systems 4.0 under Uncertainty" comes as close second [118]. Briefly after presenting a literature overview of existing evaluation models, the authors deepen model-related aspects commencing with the evaluation method. The objective of possessing an optimized manufacturing system 4.0 can only be ensured with the support of an effective evaluation process. Based on five steps, which encompass definition and scope of the evaluation, criteria selection and data collection, model definition, model execution as well as result analysis, the authors follow the goal to deliver a proper functioning assessment model. First among the concerns, the evaluation object should be established.

Having clarified the assessment object, the time span as well as additional alternative possibilities are taken into consideration. The named pre-requisites set the boundaries, which enable the definition of criteria according to the company strategy. Fundamentally, two typologies can be distinguished, namely monetary criterions like profitability or manufacturing system investments and quantitative or qualitative non-monetary criterions such as the transformability and responsiveness of manufacturing systems. To execute the analysis, the essential data belonging to the established criterions have to be collected. In other words, a unique and accurate data pool is needed.

At this point the model definition comes into play. Perceived as the most challenging step, the model establishment can be subdivided into three elements, which are respectively the modelling of uncertainty, monetarization and finally the aggregation combined with the display. Concerning the monetary and the quantitative non-monetary criterions, two modelling approaches, namely the direct modelling or the stochastic modelling, can be taken into consideration. In contrast, qualitative non-monetary criteria require according to their state a different approach that is constituted by the fuzzy set theory. Due to the self-evident financial impact related to monetary criterions, the monetarization steps are executed only for the non-monetary criterions. In this case the uppermost objective is represented by the analysis of the financial impact grounded on several causals. The last stage constituted by the aggregation requires the implementation of the Monte Carlo Simulation of the net present value (NPV). In order to facilitate the comprehension, it is essential to bear in mind that the Monte Carlo Simulation is a compendium of computational algorithms, which exploits re-enacted random sampling to generate a numerical result [119].

In addition to that, the concept of NPV is explained. Strictly speaking can be stated that the NPV is a profit calculation, which subtracts the cash outflows from the cash inflows belonging to the present value [120]. To conclude the results are presented in form of histograms or evaluation portfolios. The completion of the model definition allows to pass to the subsequent stage, which is entailed by the model execution. In this case, the authors suggest utilizing a suitable software such as MATLAB for the execution of the calculation. In addition, a sensitivity analysis is executed in order to establish the impact of several changes in the input. After the accomplishment of all the listed steps the results are displayed in the preferred manner. Figure 10 summarizes graphically the presented assessment model.

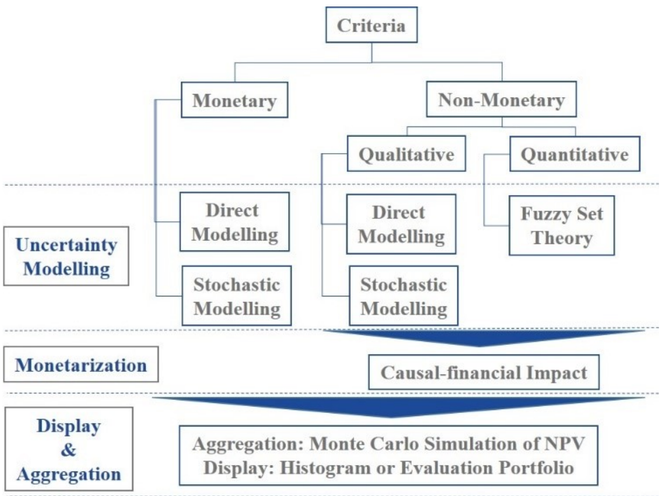

Figure 10: Structure of the first assessment model (adapted from [118]).

2.5.3 Available maturity stage models of Industry 4.0

The last sub-section belonging to the second chapter follows the aim to depict two maturity models. In this light, the research works “A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises” and “Construction of cyber-physical system-integrated smart manufacturing workshops: A case study in automobile industry” are taken into account. In advance can be confirmed that similarly to the previously treated models, the first maturity stage model considers a wider view entailing the entirety of the enterprise, whereas the second listed model possesses a focal point that is portrayed by the manufacturing workshop perspective. In this regard, the extension of the thematic area earmarks the sequence of model treatment.

The first work published by Schumacher et al. illustrates, after a concise introductory phase, an overview of existing maturity and readiness models [121]. A total of five exemplars are scrutinized qualitatively. The performance of the rough assay does not target the realization of a ranking among the existing model, but simply follows the purpose to demonstrate the persisting fundaments on which the novel maturity stage model is grounded. Concerning the methodology, the authors exploit the Becker-procedure, which relies on a multi-methodological development approach, for the composition of the model. The elaboration is subdivided into three diverse phases, which imply the comprehension of the Industry 4.0 domain through a literature review and expert interviews, the structuring of the model including the determination of maturity items and conclusively the realization of an applicable tool. The execution of the initial phase allowed to determine on the whole 62 maturity items, which are clustered into nine enterprise dimensions. The last mentioned are specified as “strategy, leadership, customers, products, operations, cultures, people, governance as well as technology” [121]. To clarify the announced dimensions few examples are quoted. Each item is recordable through a five-tier evolution, in which the lowest stage or the first level symbolizes a complete absence of entities supporting Industry 4.0 and the uppermost stage or the fifth level stands for the benchmark attributes. To accomplish the measurement, determination as well as visualization of the Industry 4.0 maturity of a company, a user-friendly software instrument based on a three-step procedure logic has been properly designed. In order to supply analyzable data to the software tool, an evaluation that is applicable in industrial environments has been executed through a standardized questionnaire. In this regard, the maturity item is presented in form of a question, whereas the five maturity stages are eligible by means of five checkmarks. During the completion of the questionnaire, experts claimed that the maturity items are not equipped with equal relevance grades, so that an additional rating has been included in the conclusive evaluation procedure. The filled questionnaires are scrutinized and the overall maturity level is established through a formula that implies the division between the sum of the weighted maturity item score and the sum of the weights. To prove the validness of the realized maturity stage determination tool, the implementation in a real industrial environment has been executed and presented in form of a case study. Figure 11 summarizes graphically the presented maturity model.

Dimension	1.0	2.0	3.0	4.0	5.0	Score	Weight
Strategy						S1	W1
Leadership						S2	W2
Customers						S3	W3
Products						S4	W4
Operations						S5	W5
Culture						S6	W6
People						S7	W7
Governance						S8	W8
Technology						S9	W9

Figure 11: Structure of the first maturity model (adapted from [1]).

Also the second work, which deals with manufacturing workshop, comprises a case study that describes the testing phase in a real industrial environment. The authors of “Construction of cyber-physical system-integrated smart manufacturing workshops: A case study in automobile industry” emphasize significantly the relevance of the applicability of the maturity model, which is elucidated by the structure of the research work [122].

Almost two third of the publication is devoted to the illustration of the case study. However, objective of the performed analysis is still devoted to the development and structure of the model. In contrast to all the other scrutinized works Zeng and Ming do not opt for the performance of a systematic literature review. After few considerations concerning the fourth industrial wave, the framework of smart manufacturing workshops is immediately illustrated. By means of an intensive collaboration with entities operating in the most diverse industrial sections, a universal framework for smart manufacturing workshops, which is based on a five-layer structure, has been determined. The primal plane is represented by supporting technologies that aim to solve particular problems and support the creation of components. Several example are cited such as sensing technologies or precision manufacturing technologies.

Climbing up the hierarchy ladder of the presented framework, the layer “basic components” appears. The named layer is composed of software or hardware that can be classified into automatic equipment, flexible fixtures, smart software, sensing and communication networks. Such essential components are followed by function modules; whose objective consists in the execution of specific tasks. A total of eight modules including “Automatic Loading and Unloading Systems (ALU), Leveled and Balanced Mixed Flow Production (LBM), Parameters Optimization System (POS), Real-time Monitoring System of Production Process (RMP), Digital Logistic Tracking System (DLT), High-Precision Online Testing and Inspection System (HPD), Automatic Fault Diagnosis and Warning (AFD), and Integrated Information Systems (IIS)” have been identified [122]. After the function models, the operational layer comes into play, in which digitalization, flexibility, re-configurability, leanness as well as agility of processes are taken into account. The business layer constitutes the conclusive plane of the framework. The main purpose is to define the business objective that can be epitomized by mass customization, personalized production and individualized customer service. The illustrated layers allow the composition of a smart manufacturing workshop. However, two important elements, namely the collaborative work mode and the transmission, sharing rules as well as mechanisms of information and data, that act as guarantor for the proper functioning of the entire system have to be integrated in the system. The first element follows the objective of harmonizing two adjacent layers, whereas the second one offers support in data interface problems.

Having created a common knowledge base that has been enriched through executed expert interviews, allows to pass to the actual creation of the maturity model. The presented five-level maturity model is grounded on eight dimensions, which are represented by the previously established function modules. Every dimension is evaluated according to a specifically designed five-tier scale, so that the maturity degree can be determined. Depending on the typology of the considered industrial entity, dimensions are weighted according to the sector-specific relevance. By means of the Analytic Hierarchy Process (AHP), which is a mathematical methodology implemented for structuring and examining particular arbitrations, a significant score associated with each dimension is calculable. The final maturity level is epitomized by the sum of the single score values. The last step consists in the visualization of the result with the support of a spider diagram. Subsequently, great importance is provided to the application of the tool in a real industrial environment. Figure 12 summarizes graphically the presented maturity model.

Level	1.0	2.0	3.0	4.0	5.0	Score	Weight
ALU	Manual	Assistant	Stand Alone	Automatic	Self-Adaptive	S1	W1
LBM	Handicraft	Stationary	Flexible	Reconfigurable	On Demand	S2	W2
POS	None	Experience	Guidebooks	Expert System	Autonomous	S3	W3
RMP	None	Artificial	Monitor	Control	Smart Decision	S4	W4
DLT	None	Manual bill	Single Record	Data Sharing	Controllable	S5	W5
HPD	None	Manual	Tool Assisted	Offline Digital	Online Digital	S6	W6
AFD	None	Passive	Stand Alone	Offline Digital	Remote	S7	W7
IIS	None	Stand Alone	Data Sharing	Process Integration	Fully Integrated	S8	W8

Figure 12: Structure of the second maturity model (adapted from [122]).

2.6 Conclusion of the second chapter

The second section of the master thesis serves as theoretical backbone of the academic work. In a first step, the focus lies on providing a thorough overview of the industrial revolution history as well as on the definitions of Industry 4.0 and related terms. In order to accomplish the illustrated step, determinations of renowned institutions as well as experts are taken into consideration. The completion allows to pass over to the fundamentals of Industry 4.0, which are treated in detail. Especially, the delineation of concepts like CPS, IoT, Big Data, Smart Products, Connectivity, Additive Manufacturing, Automation, Digitalization, Work 4.0 as well as the Safety and Security are incorporated. The presence of a robust level of knowledge permits to concentrate on the individuation of opportunities and threats associated to the last industrial revolution. For each section of the SWOT-analysis a minimum of five characteristics are underlined. The conclusive section of the chapter, which is dedicated to the state of the art, depicts an outline of existing assessment models and maturity stages models. By generating a common knowledge base related to general assessment and maturity stage models, the pre-requisites that allow to put the emphasis on industrial models are generated. To establish respectively two assessment models and two maturity stage models, a brief literature analysis is conducted. Finally, for each typology of model, a general and theme-centered prime example is analyzed accurately, with the purpose of comprehending the entailed structure as well as the implemented procedure.

Chapter 3

SYSTEMATIC LITERATURE REVIEW FOR IDENTIFICATION OF INDUSTRY 4.0 ELEMENTS

Commencing with the research methodology and approach, in which a solid theoretical base is elaborated, the systematic literature review is conducted in the third section. The relevance of the literature review immediately catches the eye by observing the related output. In concrete, the analysis allows to individuate a valuable record collection from which elements epitomizing individual components of the assessment model are extracted. The accomplishment of the listed passage and the definition of dimensions and categories of Industry 4.0 elements, enable the creation of the fundaments for the assessment model.

3.1 Research methodology and approach

The initial step towards the successful development of an Industry 4.0 assessment tool is represented by the meticulous execution of a systematic literature review. Provided the fact that the methodological structure associated with systematic literature reviews offers an adaptable framework, which intensively depends on the investigated subject area, reviews published within the years 2016 and 2017 that cover exclusively the topic of Industry 4.0, are taken into consideration. Astonishingly, a modest number of four reviews are individuated, whose substance will be exhaustively treated.

The first research work was released in the year 2016 by Hermann et al. under the title of “Design Principles for Industrie 4.0 Scenarios: A Literature Review” [123]. The systematic literature review pursues the objective of providing a common specification of Industry 4.0, which enjoys the approbation of the academic and industrial environment. To generate the definition, a total of six design principles, which are respectively represented by interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity, come into question [123].. Besides the target of the research work that is of secondary relevance, the analysis directs the attention to the utilized databases and the structure of the performed literature review. The authors opt for starting relatively a high number of publication database engines, including CiteSeerX, ACM, AISeL, EBSCOhost, Emeralds Insight and Google Scholar [123]. To obtain presentable results, the search query is grounded on a combination of two keywords.

The first one contains the English and German version of the substantial term, namely “Industry 4.0” and “Industrie 4.0”, whereas the subsequent one is clearly better equipped by means of Cyber-Physical Systems, Cyber-Physikalische Systeme, CPS, Internet of Things, Internet der Dinge, Smart Factory, intelligente Fabrik, Internet of Services, Internet der Dienste, Smart Product, intelligentes Produkt, M2M, Machine-to-Machine, Big Data and Cloud [123]. Also, in this case the bilingual keyword strategy is put into practice. The output of the query is scrutinized with the intent of establishing the number of times keywords occur in research works. According to the analysis, the authors state that four key components related to Industry 4.0 could be identified, namely Cyber-Physical Systems, Internet of Things, Internet of Services and Smart Factory [123]. By and large can be pointed out that the conducted literature review is unsophisticated and with regard to the structure strikingly plain. In addition, the number of occurrences related to key terms does not justify the inference that the determined four established elements are factually key constituent of Industry 4.0.

However, the inclusion of German terms in the search query is considered as positive aspect due to the fact that the epicenter of the fourth industrial revolution lies in the Anglo-Saxon country.

Subsequently, the attention is put on “Industry 4.0: A Survey on Technologies, Applications and Open Research Issues” published by Lu in the year 2017. The mentioned paper conducts a comprehensive review on the fourth industrial revolution and presents an overview of the content, scope and findings of Industry 4.0. The existing literature ascertained by means of two databases, which are respectively Web of Science and Google Scholar, is scrutinized. The study follows the “two-state approach initiated by Webster and Watson to conduct a literature review”. This approach has the “capability of locating rigorous and relevant research and guaranteeing the quality and veracity of the finally selected articles” [124]. Initially, “Industry 4.0” is chosen as the keyword to search published papers from 2011 to 2016 [58]. As a subsequent step a total number of 103 papers is carefully scrutinized and non-pertinent papers are excluded from further analysis. 88 papers belonging to the final selection are directly grouped into five research categories, which are represented by concept and perspectives of Industry 4.0, CPS-based Industry 4.0, interoperability of Industry 4.0 and key technologies of Industry 4.0 and applications of Industry 4.0 [58].

After deepening the illustrated research categories, the author puts enhanced emphasis on the critical issue represented by interoperability in the era of the latest industrial revolution. As an outcome of the analysis, a proposal for a conceptual interoperability-framework associated to Industry 4.0 is illustrated. To conclude the research work, concerns and tendencies of future research on the novel industrial phenomenon are discussed. Concentrating once more on the literature review, it can be mentioned that several aspects such as the excluding and including criteria that lead to the result of 88 research works are not treated and motivated properly. Compared with the previous research work, Lu emphasizes the establishment of a thoughtful structure. Despite this fact, the inclusion of interoperability and the definition of research categories is perceived as particularly interesting.

Strozzi et al. pursue a different approach within “Literature review on the ‘Smart Factory’ concept using bibliometric tools”, which was released in the prestigious International Journal of Production Research [125]. The objective of this paper consists in the representation of the landscape associated with the body of literature associated to the concept “Smart Factory”. In order to achieve the predefined target, a dynamic methodology called “Systematic Literature Network Analysis” (SLNA) has been applied [125]. Before initiating the implementation of the two-part analytical tool, the potential of Web of Science and Scopus is exploited to create a well-funded research work base.

In the first phase a systematic literature review is performed. The determination of the scrutinization-scope is established through three steps, which are composed of scope of the analysis determined by means of the Continuous Intensity Map Optimization (CIMO) approach, locating studies “keywords, time, type of documents, language” and finally the study selection and evaluation through the determination of inclusion and exclusion criteria. The accurate execution of the steps enables to create a set of suitable papers, which is perceived of vital importance for the continuation of the methodology implementation.

The second phase of the SLNA methodology consists of the bibliographic network analysis and visualization. In particular, in this section of the work, the citation network and the keywords network move into the spotlight. The mentioned networks are generated by adopting different software packages. Sci2 supports the geospatial, topical, temporal and network analysis as well as the visualization of data-sets, whereas Pajek is utilized to represent and study the citation networks that are clustered with the aid of VOS Viewer. In contrast to previously scrutinized research works, the academic work of Strozzi et al. is characterized by the application of different bibliometric software for the analytical purposes as well as well the meticulous structuring. However, it can be stated that the realized research is based on the complex analytical methodology SLNA that is implementable only and only if a profound expertise and experience is present.

Conclusively, “Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal” of Liao et al. is introduced [126]. The illustrated paper was published in the year 2017 in International Journal of Production Research. The academic work aims at compensating the lack of a missing systematic literature review of the state of the art belonging to Industry 4.0. Serving the purpose of filling the substantial gap, access to the measurement of the innovative progress associated with the new phenomenon should be provided. In order to ensure the quality of the literature review, the authors decide to capitalize solely on papers, whose pertaining journals are acknowledged as renowned sources in the Industry 4.0 thematic area. The central issue of the data analysis is qualitative phrased exploiting four sub-questions [126]:

1. Which are the enabling features of Industry 4.0?
2. Who is working on Industry 4.0, when and where?
3. What are the main research directions and the current research efforts?
4. What are the existing Industry 4.0 application fields?

Observing the listed queries, the objective of the publication, which is epitomized by the composition of a research agenda centered on the latest industrial revolution, catches the eye. To achieve the determined objective, the authors opt for a well-structured analysis consisting of five parts. Primarily, the definition of three review principles, which should eliminate the subjectivity associated with the assessment, is conducted. Starting with the first principle, an appropriate explication of inclusion and exclusion criteria is supplied. Particular focus is set on exclusion criteria that comprise the search-engine reason, the absence of a full text and conclusively the non- or loosely relation of papers with the industrial subject matter.

While the last two exclusion criterions do not require additional explanation to be comprehensible, with respect to the primal, the same statement does not hold. Indeed, the utility of search-engine reason consists in the elimination of papers that demonstrate a discrepancy between languages of the authored title or abstract and full text. To express it straightforwardly, papers that exhibit English title or keywords, but a different language with regard to the full text are excluded.

Passing over to the antagonistic typology, the inclusion criteria authorize the consideration of papers that are partially or fully related. Although the subsequent review principle is characterized by a profoundly disparate nature, key emphasis is placed on the deletion of subjectivity. Hence, an objective review strategy is put into practice. Concretely, the implementation of two researchers is required. In situations characterized by a lack of univocal consensus, a third impartial researcher acts as decision maker. In conclusion, the last listed principle is termed as data collection with evidences, which implies “that for the collection of particular data that require subjective judgments, the original supporting text descriptions of the paper should also be gathered as notes into the database” [126]. The specification of the three basic principles, serves as pre-requisite for the application of the systematic review method. In particular, a mixed approach composed of qualitative and quantitative method is put into practice. The examination is structured by following the method outlined in the Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) Statement [126]. Four sections represented by the identification, screening, eligibility and the inclusion are passed through to establish the final number of papers scrutinized in the quantitative and qualitative analysis.

At this point of the paper, the collection comes into play. Employing the databases SCOPUS, Web of Science and Science Direct, a founded base is arranged [126]. The search string is comprised of the operator "or" in between of the following four terms, namely "the fourth industrial revolution", "the 4th industrial revolution", "Industry 4.0" and "Industry 4.0". Only English papers released until June 2016, containing the search terms in abstract, title or keywords, and published in journals, conference papers, proceedings or book series are taken into consideration [126].

From the entirety of 224 paper, which forms the literature base, two typologies of information are extracted and inserted in the database. On the one hand the paper titles, paper keyword, electronic database, source-based categories (journal with SCImago categorization and impact factor or conference paper with conference name and year) and on the other hand, data related to the previously determined sub-questions, are of interest. To conclude the exhaustive systematic literature review, the data analysis is carried out through the application of qualitative and quantitative methods. Before the initiation of the execution, statistical and graphical data description as well as three qualitative pre-process procedures are applied. Concretely, the data "denoising" consisting of a preliminary passage to harmonize data expressions, is introduced [126]. The denoising step is immediately followed by the qualitative and quantitative data clustering. It is relevant to underline the fact that the second clustering makes use of ATLAS.ti5, a tool employed to extract word frequencies from text descriptions.

In regard to the consecutively performed systematic literature review, the last presented research work is perceived as precious guideline. However, provided the fact that several aspects are treated with an extremely high detail grade, Liao et al. offer a valuable and reliable orientation assistance.

3.2 Systematic literature review on Industry 4.0

Performing an analysis on systematic reviews related to Industry 4.0, allows to establish an orientation framework that functions as particularly valuable guideline for the execution of the five-phase literature examination. Commencing with the determination of the research objective and the rough records collection, successively the final records collection is fixed by means of the screening and the eligibility process.

The conclusive part of the sub-chapter is devoted to the data analysis. Grounded on an amalgamation of qualitative and quantitative methods, which is respectively underpinned by powerful software, the research objective consisting of the determination of Industry 4.0 elements is achieved. The execution of the literature review is vital for the quality of the developed Industry 4.0 assessment model. On this account enormous attention is placed on this step.

3.2.1 Definition of research objectives

As stated in the concise prefatory note, the preliminary step of the implemented systematic literature review is characterized by the determination of the research objectives. Principally two objectives are followed. On the one hand a profound insight on the state of the art related to the thematic area Industry 4.0 should be gained, and on the other hand a solid base for the subsequent construction of the assessment model for industrial companies has to be provided. Following the principle exhibited by Liao et al., a series of research sub-questions is identified with the purpose of formulating in explicit terms the pursued objectives [126]. In order to cover them as well as possible, a two-part classification of sub-questions is prepared.

The first category deals with the concepts of Industry 4.0, whereas the second one puts enhanced emphasis on the enablers. In other words, concepts are perceived as integral components of the novel industrial phenomenon, contrarily to enablers, whose function consists in the promotion and support of Industry 4.0. Besides the realization of the category, a further classification of specific elements is of interest.

With respect to concepts a breakdown into typology and thematically cluster is performed, while the enablers are organized according to clusters, interdependency among each other and implementation order. To clarify the provided explanation, the research sub-questions are straightforwardly illustrated as follows [126]:

1. Which are the concepts of Industry 4.0?
   1.1. How can concepts be classified by their typology?
   1.2. How can concepts be thematically clustered?

A closer look on the defined research sub-questions reveals the intention of the executed systematic literature review, namely the composition of a exhaustive overview and classification of Industry 4.0 concepts and enablers.

3.2.2 Definition of the framework related to the systematic literature review

The ultimate determination of the research objective allows to go on to the successive point, which is characterized by the establishment of the boundary conditions related to the systematic literature review. Leaning on the research work performed by Liao et al., three review principles are specified with the aim to delete the subjectivity attributable to the human-based review conduction [126].

Factually, several exclusion and inclusion criteria are established. Commencing with the inclusion criteria, which represent the better equipped criteria typology, a total of nine inclusion features and their acronyms are presented. Concretely, the publication database (PD) relies on the fact that only papers contained in the publication database Scopus are taken into account. In order to achieve theme-centered results, the initial search string (SS) obligatorily has to contain the key term “Industry 4.0”.

The quality of the output, is ensured through the third inclusion criterion that puts emphasis on the relevance of the source type (ST). Indeed, exclusively papers released in journals are taken into consideration. In addition, to detail the issue related to the papers or document type (DT), merely articles, review and articles in press are perceived as objects of study.

The cover period (CP) requires that papers released between the years 2011 and 2017 are taken into account. Although the German industrial nation is considered as one of the principle drives of the latest industrial revolution, it has been decided to capitalize on English documents. The language (L) is directly followed by the inclusion feature that deals with the subject area (SA). Even though the search string already acts as fine filter, a complementary reduction of the thematic realm is achieved by means of the subject area. The last named entails a wide range of disciplines that are represented by engineering, computer science, business, materials science, decision sciences, management and accounting, social sciences, , energy, econometrics and finance, multidisciplinary, economics and psychology. The broad range of the subject area has been shaped consciously in the illustrated manner, to maximize the probability of detecting valuable Industry 4.0 concepts or enablers. In conclusion, the criteria moderately pertinent (MP) and firmly pertinent (FP) are presented. As the terminology certainly reveals, the mentioned criterions cover the connectedness with the industrial phenomenon.

Passing over to the exclusion features, two attributes have to be listed. Documents that are not able to exhibit text or information completeness are not further considered. Expressed in other words, the source type completeness (STC) has to be guaranteed. The last treated criterion is the non-pertinent (NP) one. The function of this feature should prevent the observation of papers, whose research efforts do not put emphasis on Industry 4.0 in general or related thereto concepts and enablers.

Table 1 outlines the introduced inclusion and exclusion criteria.

Criteria	**Criteria description**
Inclusion	
Publication Database (PD)	Papers contained in the publication database SCOPUS are taken into account.
Search String (SS)	Search string is constructed through: "Industry 4.0"
Source Type (ST)	The research efforts published in journals are considered.
Cover Period (CP)	The research work that was published from the year 2011 to the year 2017.
Document Type (DT)	Articles, Reviews and Articles in Press are considered.
Language (L)	Papers published in English language are considered.
Subject Area (SA)	Papers belonging to Engineering, Computer Science, Business, Materials Science, Social Sciences, Decision Sciences, Management and Accounting, Energy, Econometrics and Finance, Multidisciplinary, Economics and Psychology are considered in the search.
Moderately Pertinent (MP)	The research endeavors of a paper that are dedicated to Industry 4.0 in general or have another focus than concepts and enablers of Industry 4.0.
Firmly Pertinent (FP)	The research efforts of a paper that explicitly describe concepts or enabler of Industry 4.0

Exclusion	
Source Type Completeness (STC)	Papers that do not comprise text or information completeness
Non-Pertinent (NP)	The research efforts of a paper that do not put emphasis on Industry 4.0 in general and specifically on concepts and enablers of Industry 4.0

Table 1: An overview of established inclusion and exclusion criteria.

The second measure that is put into practice with the scope of reducing subjectivity to a minimum degree, is termed as objective review strategy. Concretely, the implementation of two researchers is required. In situations characterized by a lack of inexplicit consensus, a third impartial researcher assumes the role of the decision maker.

In conclusion, the last principle, which is termed as data collection with evidences, is depicted. In particular, it implies that "for the collection of particular data that require subjective judgments, the original supporting text descriptions of the paper should also be gathered as notes into the database" [126]. The implementation of the listed measure ensures completeness and facilitates the comprehension of the selected documents [126].

3.2.3 Determination of the systematic literature structure and method

The structure and the implemented method related to the review, strongly relies on the principles defined by three experts, namely Tranfield, Denyer and Smart, whose primary research epicenter rotates around the determination of efficient systematic literature review methods. In their paper "Towards a methodology for developing evidence-informed management knowledge by means of systematic review" they do not only underline the relevance of the accuracy associated with literature review, but also offer a transparent vade mecum for its realization [127]. The systematic literature review profoundly differentiates from the classic literature analysis. In particular, the presence of a comprehensible and scientific procedure enables the minimization of subjectivity in scrutinizing variegated typology of literature.

In addition, it functions as appreciated theoretical guideline for the review during the conduction. The authors point out that the presented methodology incorporates affine techniques in order to guarantee the persistence of an evidence fundament. Beyond all, the meta-analysis has to be introduced. The synergy between the mentioned methodologies provides an excellent complement and therefore a full-features evaluation tool. Whereas the systematic literature review is centered on the establishment of key documents belonging to the thematic area of interest, the meta-analysis, provides an analytical process to determine an outline of studies and related contents without putting exaggerated emphasis on singular literature entities. Provided the fact that Tranfield et al. do not recommend any specific meta-analysis form, the methodology presented in the previously detailed review research work of Liao et al., namely the meta-analysis grounded on the PRISMA statement, is exploited.

The effective guideline that was finalized in 2005, consists of a "27-item checklist and a four-phases flow diagram" [128]. Whereas the checklist follows the purpose to supply valuable hints, the four-phases epitomize the substantial structure of the analysis. Starting with the identification, a rough collection of all the records is realized. The screening delineates the initiation of the filtering process by means of the application of the inclusion criteria represented by ST, CP, DT, L, SA and STC. Passing over to the eligibility of screened records, all the exclusion criteria come into play. In conclusion the determination of the final record collection is realized through content-centered inclusion criteria, which are respectively MP and FP.

1. Phase: Definition of the research objectives through research questions
(1.0) Which are the concepts of Industry 4.0? (1.1.) How can they be classified by their typology? (technology, methodology, tools and methods) (1.2.) How can they be thematically clustered? (level I, level II, …)
2. Phase: Identification of the rough records collection
Records identified through database SCOPUS searching (PD) by utilizing the search string "Industry 4.0" (SS)
Counts: 733
3. Phase: Screening of rough records collection
Records excluded due to the implementation of the mentioned criteria: - ST (nr. 20) - CP (nr. 2) - DT (nr. 317) - L (nr. 141) - SA (nr. 115) - STC (nr. 5)
Counts: 133
4. Phase: Definition of eligibility of selected records collection
Studies determined in order to guarantee the eligibility of the records - NP (nr. 31)
Counts: 102
5. Phase: Determination of final record collection
Studies that form the final record collection classified according to: - MP (nr. 75) - FP(nr. 27)
Counts: 27

Figure 13: Structure and numerical results of the executed systematic literature review.

Figure 13 provides an overview of the review structure and reveals already the outcome of the performed scrutinization, which is treated in the successional sub-chapters.

3.2.4 Identification and screening of the records collection

The determination of the research objectives combined with the establishment of the systematic literature review structure, are essential pre-requisites for the proceeding of the evaluation process. Commencing with the identification of a rough records collection, two inclusion criteria, namely the publication database and the search string are deployed. A massive base composed of 733 entities is obtained by employing Scopus and the search string “Industry 4.0”. The successfully concluded second phase authorizes the initiation of the screening procedure. One by one, a combination of inclusion and exclusion criteria exerts the ability of marginalizing unsuitable records. In the pictured application, most inclusion criteria and one exclusion feature including source type, cover period, document type, subject area and conclusively source type completeness are utilized effectively with the noteworthy result consisting in the elimination of 600 papers. Particularly, the document type, language and the source type completeness stick out from the mass by contributing with a total number of eliminations that touch 573 counts. Accordingly, an intermediate result of 133 counts can be noted.

3.2.5 Definition of eligibility of selected records

Whereas the execution of the second phase is characterized by an almost negligible error probability by virtue of the straightforward and objective nature of the exhibited criteria, the same cannot be state with regard to the fourth phase. Indeed, the performance of the eligibility asks for the implementation of the remaining exclusion criteria. By means of the non-pertinent criterion, which relies on a qualitative analysis of the researcher, a modest amount consisting of 31 papers is excluded from further considerations. The conduction of those kind of analysis is not perceived as a common or elementary undertaking. In several cases, following the second review principle of the objective review strategy, the aid of the third re-searcher is demanded, who acts as impartial decision maker. Finally, a total amount of 102 records is reached.

3.2.6 Determination of final record collection

The last and definitely most challenging phase of the systematic literature review faces the classification of the final records collection. In the specific application case, the residual inclusion criteria represented by the moderately pertinent and firmly pertinent criteria come into play. Starting with the final records collection of 102 entities, 75 are perceived as moderately pertinent, in spite of the remaining 27 that belong to the firmly pertinent sphere. It has to be pointed out that also in the determination and in particular the attribution of the final record collection to a criterion the commitment of the decision maker assumes an essential role. Provided the fact that the performed evaluation has been accomplished by researchers relying on a qualitative approach, the complete absence of errors cannot be entirely omitted. However, the objective review strategy, the accurately defined structure as well as the rigorous implementation of the systematic literature review allow to determine a qualitative fundament for the successive proceeding of the assessment model development.

3.2.7 Descriptive sample overview

In order to complete the subchapter 3.2 devoted to the systematic literature review on the thematic area of Industry 4.0, a qualitative and quantitative data analysis methodologies are applied. Initiating with the qualitative data analysis, the functionalities of VOS Viewer, which is a software tool for constructing and visualizing bibliometric networks, are exploited. Concretely, an analysis of the record collection with the purpose of discovering links between texts, authors and countries is conducted. Figure 14 shows the result of the VOS viewer text analysis.

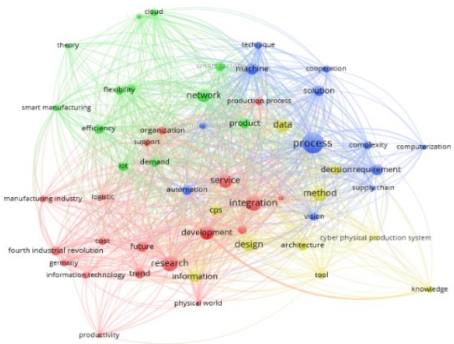

Figure 14: Text analysis performed with the software VOS viewer.

Observing the presented graphical outcome of the VOS Viewer text analysis that considers abstract and full-text, it can be argued that process, research, service, integration, development and network are terminologies characterized by an enhanced grade of importance. Factually, the size of the sphere symbolizes the relevance of the term. VOS Viewer classifies the sum of terms into four clusters, which are respectively epitomized by the research cluster (red), the information technology-cluster (yellow), the network-cluster (green) and the process-cluster (blue). The numerous links between terms is the evidence of the entanglement of the concepts.

Passing over to the authors, it has to be noted that only academics that have published more than ten topic-related works are included in the analysis. Figure 15 presents the result of the VOS viewer author analysis.

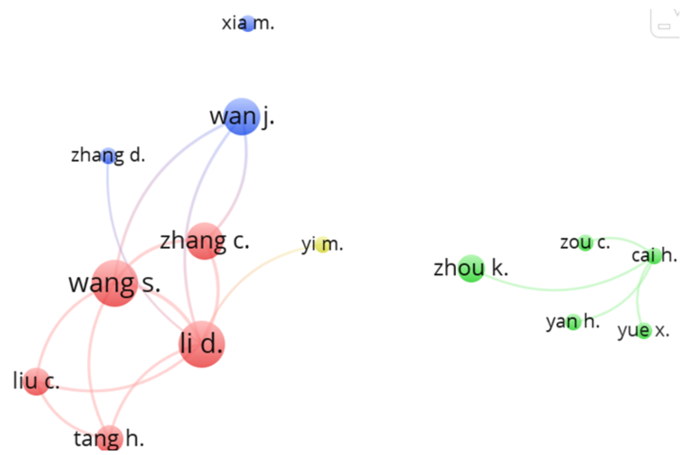

Figure 15: Authors analysis performed with the software VOS viewer.

To complete the qualitative examination, information regarding the countries are extracted. As expected, three countries, namely Germany, United States as well as China dominate the Industry 4.0 landscape. However, also France, Mexico and India assume an important role. Figure 16 depicts the result of the VOS viewer country analysis.

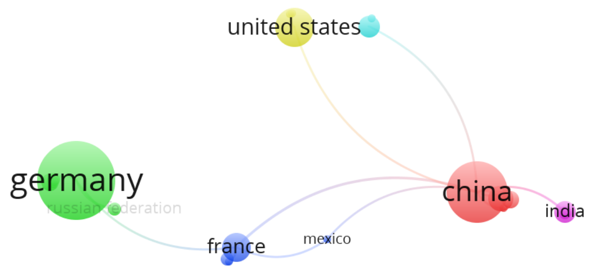

Figure 16: Country analysis performed with the software VOS viewer.

The completion of the qualitative data analysis allows to continue with the quantitative data analysis. Especially two information are of interest. The first one is related to the number of publications released in each year and the second one demonstrates by observing the number of papers released in the mentioned journals, which are the most relevant peer-review sources for Industry 4.0. The statistical analysis could undoubtedly supply a vast variety of information, but yet to minimize the risk of overshooting the analysis a limitation to the named realms is respected.

Figure 17 demonstrates that Industry 4.0 is considered as a trendy subject area, whose relevance is enhancing in the course of the years. The execution period of the systematic literature review, which has been concluded in August 2017, serves as explanation for the modest number of publication in the year 2017. However, after having conducted a brief search focused on the current year, it can be con-firmed that the continuously positive increasing trend subsists.

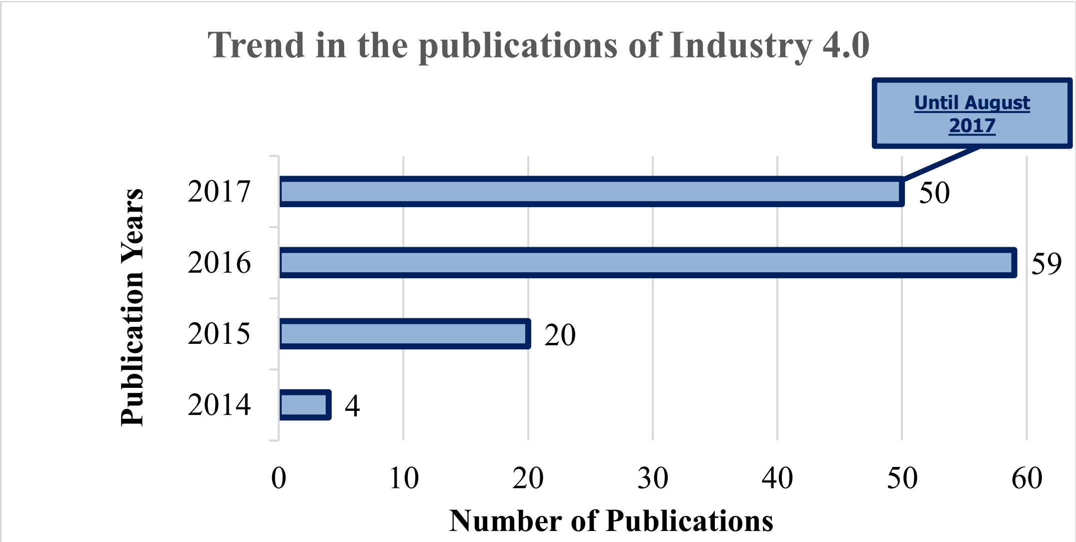

Figure 17: Diagram of number of publications per years.

Concentrating on the examination with regard to the source title, it can be stated that IFAC-PapersOnLine possesses the highest number of publications centered on Industry 4.0. Journals exhibiting less than three publications have been omitted in order to guarantee a higher representation clarity in Figure 18.

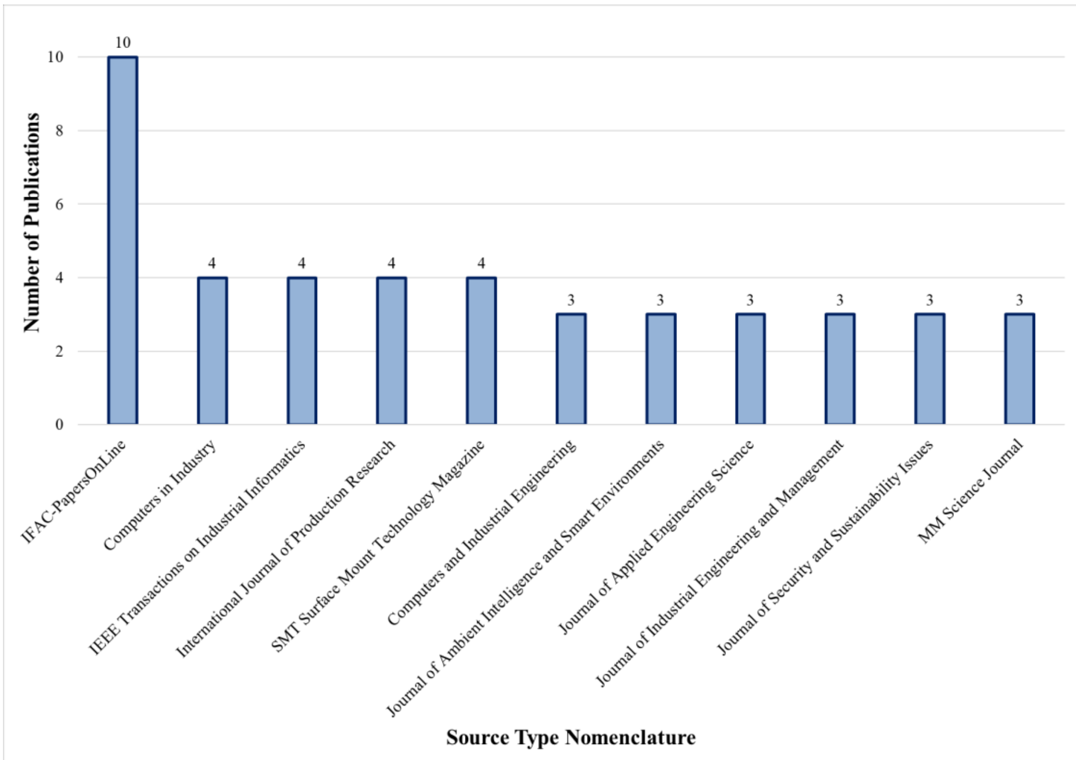

Figure 18: Diagram of number of publications per selected and most relevant journals.

The executed qualitative and quantitative data analysis serves as base for further and deeper evaluation that are conducted in the subsequent sub-chapter.

3.2.8 Classification and content analysis

The completion of the wide-ranging systematic literature analysis implies the presence of an outright theoretical basis that in the previous sub-chapter has been scrutinized with the aim to extract qualitative and quantitative data. At this stage of the theoretical evaluation the results consisting of a total of 103 papers are examined by means of a qualitative content analysis in order to establish Industry 4.0 elements, which will subsequently assume a vital function within the assessment model. Indeed, the last mentioned will represent the criteria according to which the Industry 4.0 grading of the companies will be executed.

The qualitative literature analysis allows the identification of a total of 75 Industry 4.0 elements. According to Gökalp et al., the singular literature findings have to be denominated with the reference term or concept of "element" due to the broad thematic diversification [117]. The scattered nature of the established Industry 4.0 elements requires the introduction of a clear-cut structure, whose objective consists in the creation of a thematical order. In this connection, a multi-level categorization is introduced following a gradual procedure.

The primal step involves the introduction of the element-typologies. It is essential to mention that the illustrated typologies are not characterized by a direct connection to the multi-level categorization, in the sense that they are exclusively perceived as preliminary but at the same time indispensable condition, on which the successful realization of a clear-cut structure depends. The reason for the marginalization from the multi-level categorization lies in the fact that a typology is not univocally attributable neither to the components of the first level dimension nor to entities belonging to the second level dimension.

A total of seven typologies has been identified and portrayed in Table 2:

Nr.	Typology
1	Architecture
2	Methodology
3	Model
4	Platform
5	Process
6	Theory
7	Tool

Table 2: The seven typologies utilized for the initial categorization.

To promote the comprehension of the presented first rough categorization schema, each typology is exemplified. The first component is represented by the architecture, which according to O'Donovan et al. is specified as "research output that provides a theoretical view on how various components in a solution will sit together and interact" [129]. The methodology on the other hand focuses on solving a particular problem by providing a low-level approach characterized by a practical orientation instead of a theoretical one. The same cannot be claimed for the model, which strives for an excellent balance between theory and handy application. Indeed, models are defined as “research outputs that produces mathematical models for solving particular problems”. The fourth typology is represented by the platform that is massively influenced by the IT-realm. It is specified as “research output that provides a system with hardware and software components, which enables applications to execute”. The process, which constitutes the fifth component of the typology classification, possesses an affinity with the methodology, due to its proximity to the practical sphere [129]. The essential distinction consists in the fact that not a mathematical model, as it is in the case of the methodology, but the development of a low-level process allows the resolution of certain issues. Passing to the penultimate typology, the theory is introduced. The terminology of the presented component already reveals all particulars of its nature, which is strongly marked by a marginal practical relevance. Finally, the tool is depicted, which similarly to the platform, is characterized by the proximity to the IT-realm. The last typology is clearly defined as “research output that develops well-defined software utilities that address a subset of a bigger problem” [129].

Particularly, the delineated overview of the criteria, according to which the typological allocation is executed, serves as structuring aid in the initial phase. However, its factual application offers support in revealing structural issues, which do not assure the presence of a transparent classification. Above all, the scarce depth of detail associated with the initial categorization scheme has to be highlighted. Indeed, it represents the primal reason that justifies the introduction of an ancillary level dimension. The uppermost objective followed by the refinement of the previously presented breakdown is to enhance the transparency associated to the Industry 4.0 elements structure. The ameliorated degree of detail is ensured by the determination of 18 subordinated outline levels. Comparing the seven previously illustrated components with the newly established subordinated outline levels, the improvement with regard to the granularity becomes noticeable. The components belonging to the second level dimension are presented in the Table 3:

Nr.	II. Level Dimension
1	Big Data
2	Business Models 4.0
3	Communication & Connectivity
4	Cyber Physical Systems
5	Cyber Security
6	Decentralization
7	Deep Learning, Machine Learning, Artificial Intelligence
8	Digital Product Lifecycle Management
9	Human Resource 4.0

10	Identification and Tracking Technology
11	Lean 4.0
12	Manufacturing 4.0
13	Monitoring & Decision Systems
14	Production Planning and Control
15	Robotics & Automation
16	Standards 4.0
17	Supply Chain Management 4.0
18	Virtual Reality & Augmented Reality

Table 3: The components of the second level dimension.

Under exact consideration of the presented second level dimension, the intense reference to the second chapter of the master thesis and in particular to the fundamentals of Industry 4.0 catches the eye. All the 18 components with exception to the decentralization concept have been treated in the course of the elaboration of the master thesis. In order to enable an exhaustive and integral insight associated to the second level dimension, the explanation of the notable aspects associated with the decentralization is submitted.

The decentralization concept is realized by means of a distributed manufacturing systems (DMS). It entails the distribution with respect to the execution of fabrication methods and customer-proximity concerning manufacturing and assembly processes [130]. The implementation of the decentralization concept within an industrial environment is on the one hand strictly related to an intensification of organizational effort, that on the other hand result in considerable economic advantages [131].

The comprehensive presentation of the second level dimension enables the initiation of the last passage belonging to the realization of the multi-level classification. Factually, the amalgamation of the 18 components is executed following the pursue of bringing the first level dimension into being. The function as superordinate level consists in the facilitation of the assignment of components to a specific thematic area of reference.

The first level dimension, which is composed of four subordinated outline levels, and the corresponding second level dimension components are presented in Table 4:

Nr.	I. Level Dimension	II. Level Dimension
1	Operation (OP)	Digital Product Lifecycle Management
		Lean 4.0
		Monitoring & Decision Systems
		Production Planning and Control

2	Organization (OR)	Business Models 4.0 Decentralization Supply Chain Management 4.0 Standards 4.0
3	Society (S)	Human Resource 4.0
4	Technology (T)	Big Data Communication & Connectivity Cyber Physical Systems Cyber Security Deep Learning, Machine Learning, Artificial Intelligence Identification and Tracking Technology Manufacturing 4.0 Robotics & Automation Virtual Reality & Augmented Reality

Table 4: Components of the first level dimension and related second level dimension constituents.

The detailed explanation associated to the systematic categorization of the established Industry 4.0 elements, enables the illustration of the comprehensive table, whose content entails the Industry 4.0 element, the first level dimension, the second level dimension as well as the typology. Table 6 offers an overview of the executed systematic literature review; whose principle scope lies in the representation of the categorized Industry 4.0 elements.

Nr.	Name	I. Dimension	II. Dimension	Type
1	5C-Architecture	Technology	Cyber Physical Systems	Architecture
2	7Epsilon	Operation	Lean 4.0	Methodology
3	Additive Manufacturing (3D-Printing)	Technology	Manufacturing 4.0	Platform

4	Artificial Self-Organizing systems	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Platform
5	Artificial Intelligence	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Platform
6	Augmented Reality	Technology	Virtual Reality & Augmented Reality	Platform
7	Automated-Storage-and-Retrieval-System	Technology	Robotics & Automation	Platform
8	Autonomous Production Control	Operation	Production Planning and Control	Methodology
9	Autonomous Guided Vehicles	Technology	Robotics & Automation	Platform
10	Cloud Computing	Technology	Big Data	Platform
11	Computer Aided Design	Operation	Digital Product Lifecycle Management	Tool
12	Computer Aided Engineering	Operation	Digital Product Lifecycle Management	Tool
13	Computer Aided Manufacturing	Operation	Digital Product Lifecycle Management	Tool
14	Continuous Flow Flexible Job Shop	Organization	Decentralization	Theory
15	CPS Architecture Model	Technology	Cyber Physical Systems	Architecture
16	E-Kanban	Operation	Lean 4.0	Tool
17	Cyber-Physical Systems	Technology	Cyber Physical Systems	Platform

18	Cybersecurity	Technology	Cyber Security	Framework
19	Digital Add-on	Organization	Business Models 4.0	Model
20	Digital Lock-in	Organization	Business Models 4.0	Model
21	Digital Twin	Operation	Digital Product Lifecycle Management	Tool
22	Dynamo (Dynamic Levels of Automation for Robust Manufacturing Systems)	Technology	Robotics & Automation	Platform
23	Education 4.0	Society	Human Resource 4.0	Theory
24	Electricity Fingerprint Analysis Technology	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Platform
25	Enterprise Resource Planning	Operation	Production Planning and Control	Framework
26	Flexibility Graphs	Operation	Production Planning and Control	Methodology
27	Global Footprint Design	Organization	Supply Chain Management 4.0	Methodology
28	High Resolution Management	Organization	Supply Chain Management 4.0	Methodology
29	Holonic Manufacturing Systems	Organization	Decentralization	Platform
30	Human Robot Collaboration	Technology	Robotics & Automation	Theory
31	Hybrid-Data-on-Tag Approach	Technology	Identification and Tracking Technology	Methodology

32	Hybrid Supply Chain	Organization	Supply Chain Management 4.0	Theory
33	Integrated Monitoring System	Operation	Monitoring & Decision Systems	Platform
34	Internet of Things	Technology	Communication & Connectivity	Platform
35	ISO-IEC Architecture	Organization	Standards 4.0	Architecture
36	Large Scale Machine Coordination Systems	Organization	Decentralization	Platform
37	Lean Automation	Technology	Robotics & Automation	Theory
38	Line Information System Architecture	Organization	Standards 4.0	Architecture
39	Logistic Mall	Organization	Business Models 4.0	Framework
40	Manufacturing Execution Systems	Technology	Identification and Tracking Technology	Platform
41	Multi Agent System	Organization	Decentralization	Platform
42	Networked CPS Architecture	Technology	Cyber Physical Systems	Architecture
43	NIST Architecture	Organization	Standards 4.0	Architecture
44	Object Fingerprint Technology	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Platform
45	Object Self Service	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Model
46	Open Innovation Models	Operation	Digital Product Lifecycle Management	Model

47	Personalized Customization Manufacturing System	Technology	Manufacturing 4.0	Platform
48	Physical Freemium	Organization	Business Models 4.0	Model
49	Physical Internet	Organization	Supply Chain Management 4.0	Theory
50	Plug and Produce Approach	Technology	Manufacturing 4.0	Tool
51	Product as a Point of Sales	Organization	Business Models 4.0	Model
52	Product Lifecycle Management	Operation	Digital Product Lifecycle Management	Methodology
53	Product-Service Architecture	Organization	Business Models 4.0	Architecture
54	Radio-frequency identification	Technology	Identification and Tracking Technology	Platform
55	RAPID Machine Learning	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Theory
56	Reference Architectural Model Industry 4.0 (RAMI 4.0)	Technology	Cyber Physical Systems	Architecture
57	Remote Usage and Condition Monitoring	Operation	Monitoring & Decision Systems	Tool
58	Science Fiction Prototyping	Operation	Digital Product Lifecycle Management	Methodology
59	Self-Learning Anomaly Detection Technology	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Platform

60	Smart Behavioral Filter	Technology	Cyber Security	Tool
61	Smart Process Manufacturing	Technology	Manufacturing 4.0	Platform
62	Smart Shop Floor	Operation	Monitoring & Decision Systems	Process
63	Structure Dynamic Control Mechanism	Operation	Production Planning and Control	Methodology
64	System Invariant Analysis Technology	Technology	Manufacturing 4.0	Platform
65	Tele-Maintenance (example: ARTab)	Technology	Manufacturing 4.0	Tool
66	Virtual Commissioning	Technology	Virtual Reality & Augmented Reality	Methodology
67	Virtual Engineering Objects	Technology	Virtual Reality & Augmented Reality	Methodology
68	Virtual Engineering Process	Technology	Virtual Reality & Augmented Reality	Methodology
69	Virtual Enterprise	Technology	Virtual Reality & Augmented Reality	Platform
70	Virtual Reality	Technology	Virtual Reality & Augmented Reality	Platform
71	Virtual Training	Technology	Virtual Reality & Augmented Reality	Process
72	Visual Analytics	Operation	Monitoring & Decision Systems	Platform
73	Volume Cycle	Operation	Production Planning and Control	Methodology
74	Wireless Sensor Network	Technology	Communication & Connectivity	Platform

75	Workload Management Systems	Organization	Decentralization	Platform

Table 5: Complete table of categorized Industry 4.0 elements.

The exhaustive and comprehensive description of the single Industry 4.0 elements is comprised in the subsequent sub-chapter.

3.2.9 Industry 4.0 elements

The determined Industry 4.0 elements are exemplified in the conclusive sub-chapter, which represents the finishing line of the section devoted to the systematic literature review. Objective of the presented descriptions is the creation of a solid and common knowledge base, which will assume a vital relevance in the development and more particularly in the actual implementation of the assessment model in industrial environments. The assessor can put the description of the Industry 4.0 elements into use with the purpose of clarifying doubts emerged in the course of the evaluation process. On this account a concise but at the same time comprehensible explanation has to be provided.

3.2.9.1 5C-Architecture

The *5C-Architecture* serves as concrete guideline in the establishment of an Industry 4.0 conform CPS [37]. The first level termed as smart connection focuses on the collection of data via sensors and controllers. Subsequently, the data-to-information conversion takes place by means of specific algorithms. The third level that is represented by the cyber level serves as information hub for all the interconnected machines. Successively, the cognition brings the human into play by allowing the visualization of the evaluated data, which are perceived as decisional basis. In conclusion the configuration is introduced. It implies the feedback process between cyber and physical sphere, which should enable the initiation of a machine-self-configuration process [37].

3.2.9.2 7 Epsilon

The *7 Epsilon* is a methodology developed for the achievement of in-process quality improvement within advanced industrial environments. The uppermost objective is represented by the establishment of a quality management system complying with the requirements expressed within the standard ISO9001:2015 [132]. The concept of 7 Epsilon offers a conceptional expansion compared to the traditional Six Sigma approach, which is characterized by a broader field of application. As the designation of the methodology suggests, a total of seven steps has to be put into practice in order to enhance the internal procedural quality. The acquisition of the procedural knowledge, forms the foundation of the 7 Epsilon methodology. Secondly, the refinement of the process knowledge has to occur. At this stage of the implementation, the penalty matrix is introduced for the analysis of the in-house process data. The fourth passage entails the derivation of hypothesis, which subsequently are utilized as base for the innovation process grounded on root cause analysis. In order to achieve concrete results, corrective actions are implemented. Finally, dedicated teams are established, whose responsibility lies in the integration of 7 Epsilon in the industrial environment [133].

3.2.9.3 Additive Manufacturing (3D-Printing)

Additive Manufacturing or 3D-Printing is specified by the ASTM as “the process of joining materials to make objects from 3D-model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [79]. In accordance with Gibson, four different typologies of material, namely polymers, composites, metals and ceramics, can be processed in several forms including powder, liquid as well as solid [85]. The application range is wide comprising prototyping, manufacturing and tooling. AM provides an answer to the increasingly critical individualization requirement by ameliorating the flexibility and the adaptability with regard to product variety and volume [131].

3.2.9.4 Artificial Self-Organizing System

Artificial Self-Organizing System (ASO) epitomizes an implementation alternative to the traditional Intelligent Manufacturing System (IMS). Compared to IMS, which is perceived as a techno-centered approach, AMS intensively emphasizes aspects associated with the human operator offering a highly reactive interaction possibility. Concretely the human-machine correlation is realized by means of a particular assistance system, which authorizes the human operator to actively shape the process control loop within the automation levels. In the traditional IMS the human comes into play exclusively in cases, where unexpected issues have to be solved. AMS offers support in dealing with intricated issues in productive environments by simultaneously enhancing the performance in terms of energy consumption, throughput and operator workload [134].

3.2.9.5 Artificial Intelligence

Artificial Intelligence (AI) is comprehended as the attribution of decision making ability to the computational systems, which replicate the reasoning of human experts [135]. The intelligent imitation capability of computer programs is retrievable in a broad range of disciplines, which entails as a matter of course also the industrial environment. Especially in the era of the latest industrial revolution, great value is placed on the thematic associated with AI, which facilitates the several operations within an enterprise. The evaluation of production data, the qualitative enhancement of production planning as well as the support of line operator by means of intelligent machines are only few application areas that evidence the daily deployment of AI [136].

3.2.9.6 Augmented Reality

Augmented Reality (AR) provides a real-time modified version of the reality, which is supplemented with virtual features entailing sounds, videos, graphics as well as GPS data [137]. The technical implementation of AR is grounded on the combined utilization of semitransparent lenses and a wearable computational device. The technology assumes a pivotal role within present industrial environments due to the supporting ability related to numerous productive operation, encompassing the maintenance of the production system [91]. The technological advances achieved with respect to the AR-technology, allow to develop affordable devices. Microsoft HoloLens and Google Project Aura, which replaces the famous Google glasses on the market, are rated among the most popular AR-devices [138].

3.2.9.7 Automated-Storage-and-Retrieval-System

Automated Storage and Retrieval System (ASRS) is defined as "an integrated, computer-controlled, and automated material handling machine for depositing, storing and retrieving loads" [139]. The operations related to the physical material management are represented by loading, storing, retrieving as well as order-picking several entities [140]. ASRS is composed of an autonomous rover and a multilevel rack structure [141]. The first constituent part represented by the autonomous rover enables the functioning of the system responsible for the order execution, reading and updating, whereas the second integral element is concerned with the actual material transfer [142].

3.2.9.8 Autonomous Production Control

Autonomous Production Control (APC) is a combination of methods as well as technologies that follows the purpose of self-dependently harmonizing production related control functions, such as order approval, identification of capacity restrictions and sequencing, in order to comply with due date deadlines [143]. While traditional production control, which is majorly based on human work, comes up against borders due to increasingly intricated structures and dynamics associated with productive areas, APC is perceived as the solution for overcoming such serious difficulties. A mixture between technologies like RFID and wireless communication systems and methods based on efficient algorithms should introduce the autonomy in the production control context [144].

3.2.9.9 Autonomous Guided Vehicles

Autonomous Guided Vehicles (AGVs) are robotic transporters, which function without the implementation of human driver units [145]. Barrett Electronics of Northbrook, a US-company whose core-competence lies in the robotic realm, firstly introduced in the year 1955 the AGVs in the international market. In the course of the decades, the spread and application of the technologies gained relevance and reached the peak in the early 2000s. The robotic transporters are mainly classified according to the implemented navigation concept that can be wired-, guide tape- or laser target-based [146]. AGVs, which are responsible for executing actions of logistical nature such as handling, loading or unloading operations, find an application in variegated typologies of industries. The automotive, pharmaceutical, chemical, food and beverage, manufacturing and warehousing are among the most relevant industrial environments [147].

3.2.9.10 Cloud Computing

Cloud Computing is defined by NIST as "a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." [148]. According to Mell and Grance the presented cloud model has to entail "five essential characteristics, three service models and fours deployment models" [148]. The essential characteristics are represented by "resource pooling, on-demand self-service, rapid elasticity and measured service, broad network access, while the three service models encompass Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS)" [148]. To conclude the deployment models consisting of community-, public-, private- and hybrid cloud are illustrated [53].

3.2.9.11 Computer Aided Design

Computer Aided Design (CAD) involves the utilization of a software, whose pursue consists in the supporting the creation, revision and analysis of a design [149]. The market introduction of the CAD-software was performed by IBM in the 1960s [150]. However, the great usability of the CAD was strictly depended on the expansion of computational technologies. Since the year 1990, the application realm has touched a wide range of industries by means two-dimensional or three-dimensional CAD programs. According to Autodesk, one of the major players that offer CAD-solutions, the software enables the performance of a variegated operations, including 3D model generation of a design, the implementation of material and light dynamics as well as the modification of document with respect to the dimensions and other specifications [151].

3.2.9.12 Computer Aided Engineering

Computer Aided Engineering (CAE) entails the deployment of computational tools in order to perform in-depth engineering analysis. The intended purpose of the named software consists in pursuing the support of computer-based object generated by means of CAD. In particular, five operations incorporating "multibody dynamics (MBD), finite element analysis (FEA), computational fluid dynamics (CFD), durability and optimization are considered as essential parts of CAE" [152]. The computational package is perceived as an essential tool in a wide range of industrial environment due to its ability of preventing issues related to manufacturing processes or produced components [153]. Several software, encompassing Autodesk Inventor, CATIA and NetLogo, are perceived as qualitative engineering simulation tool kits.

3.2.9.13 Computer Aided Manufacturing

Computer Aided Manufacturing (CAM) implies the implementation of computer-based instruments in order to control the manufacturing machinery during its operations [154]. Analogically to the CAE-concept, CAM is perceived as the complement and a continuing support to the computational components production that puts enhanced emphasis on the production machine aspects. While in past decades CAM has been equated to numerical control abbreviated as NC, today its implementation scope goes far beyond this limit by increasing the efficiency of productive processes. In concrete, waste associated to raw material utilization and exaggerated energy consumption should be avoided by means of CAM [155].

3.2.9.14 Continuous Flow Flexible Job Shop

Continuous Flow Flexible Job Shop (CFFJS) follows the objective of solving the flexible job shop problem by means of the application of a specific model, which is termed as "dedicated continuous material flow model" [156]. Within this typology of model, operations are typically depicted by proper material flow functions grounded on the integration of arbitrarily defined speed patterns. The variability associated to the speed patterns results in "position-dependent processing times and overlapping in operations, which are perceived in industrial environments as restrictive elements" [157]. Bożek and Wysocki propose a scheduling algorithm based on the elimination approach to enable a continous flow also within a flexible job shop.

3.2.9.15 CPS Architecture Model

CPS Architecture Model aims at offering a concrete implementation and construction guideline associated to CPS-systems [36]. A total of ten CPS reference architecture models are dominating the CPS-related research literature landscape, including service-based architecture model, basic prototype architecture, EuroCPS project architecture, IoT@Work project architecture, CPS architecture model proposed by Wan et al., Networked CPS architecture, ISO-IEC architecture, NIST architecture, AIOTI (EC) architecture and 5C architecture [158]. Among the listed architecture model, the one that enjoys the greatest prominence in the global industrial environments, is represented by the 5C-architecture model conceived by Lee et al. in the year 2015. As already the designation reveals, the model is composed of five levels, which are respectively represented by the "smart connection, data-to-information conversion, cyber level, cognition level and configuration level" [19].

3.2.9.16 E-Kanban

E-Kanban is considered as an electronic upgrading of the traditional Kanban system based on bins and cards [159]. Firstly, introduced by the Toyota Motor Corporation, the E-Kanban is an information system operating inside and outside of the entrepreneurial communication system, whose objective relies on the efficient order management of components [160]. The advantages with respect to the traditional approach consists in the elimination of human errors, such as wrong manual registration or loss of cards, the integration with the ERP-system, whose major benefit consists in the real-time visibility, and the optimization of inventory levels [161].

3.2.9.17 Cyber-Physical Systems

Cyber-physical systems (CPS) are conceived as the principal enabler of the fourth industrial revolution. According to NIST, CPS are defined as "co-engineered interacting networks of physical and computational components" [31]. Innovations associated to a comprehensive range of research realms, encompassing cybernetics, mechatronics and process theory, flock together and pave the way for the existence of CPS. The transformative technology strives for the amalgamation of two different worlds, which are respectively represented by the virtual and physical sphere, by exploiting the full potential of embedded software-intense systems and global networks [32]. CPS are essential in several industrial sectors, first and foremost in the automotive industry, as they enable the enhancement of safety, comfort, efficiency as well as networking quality [19].

3.2.9.18 Cybersecurity

Cybersecurity refers to the safeguarding of computational entities, encompassing hardware, software and data, from harm, misappropriation as well as abuse [162]. Concretely, the protecting practice focuses on the prevention of unauthorized access of hackers as well as of company-operators to information technology and related derivates. Within the fourth revolution movement, which has set down profound roots in the IT-world, the aspects associated with cybersecurity are receiving considerable attention in industrial environments. Acknowledged institutions, like NIST and ISO, follow up intensively with the proposal of solutions [163]. The ISO/IEC 27000 family devoted to the information security management system and the NIST-cybersecurity network are among the most relevant realized measures in the global industrial landscape [164].

3.2.9.19 Digital Add-on

Digital Add-on constitutes an aspect of a business model, in which individual or several services of digital nature are provided in the post-purchase phase belong to physical product [165]. A celebrated instance centered on digital add-ons has been the introduction of an autopilot software upgrading onto the market performed by Tesla, the leading electronic carmaker in the world. The presented add-on, which clearly demonstrates the connectedness to the digital sphere, is exclusively achievable by Tesla owner and allows after paying a fee of 2500$ to activate the autonomous parking of the automobile [166]. The US-automobile manufacture firmly believes in this aspect of business models and plans to extend the range of digital add-ons. In the near terms, Tesla aims at offering permanent or temporary performance enhancements, such as the addition of specific amounts of horsepower.

3.2.9.20 Digital Lock-in

Digital Lock-in puts emphasis on a common business model scheme, also known as "Razor and Blade business model pattern", which is a concept conceived by the enterprise Gillette [167]. The broad lines of the business model pattern rest upon a lock-in logic that confines the liberty of the customer [168]. In concrete, this signifies that the customer, is obliged to purchase original components in order to assure compatibility with the product. While Gillette focuses on physical lock-in, the IT-driven industrial revolution offers the possibility to expand the business model scheme to the digital world. The phenomenon of IoT, which relies on sensor and actuator, is perceived as an attractive implementation field for the presented model [165].

3.2.9.21 Digital Twin

Digital Twin is specified as “an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin” [169]. The defined entity is composed of three fraction, which are respectively represented by the physical entity, the virtual entity and the associated data [170]. It is essential to note that the concept of digital twin goes along with two characteristics, which are summarized as the virtual real-time rendition of the mutations experienced by the physical entity and temporal compatibility of registered data. The initiation of the fourth industrial revolution has placed the presented theme in the foreground by simultaneously enlarging its application field that has been circumscribed to the aeronautics and astronautics realm. In present days, great value is attributed to the concept of digital twin as it is perceived as solution to issues belonging to the Product Lifecycle Management abbreviated as PLM [171].

3.2.9.22 Dynamo (Dynamic Levels of Automation for Robust Manufacturing Systems)

Dynamo (Dynamic Levels of Automation for Robust Manufacturing Systems) refers to a methodology that aims at identifying an appropriate automation strategy by assessing, measuring and analyzing the degree of automation with respect to mechanical and informational labor activities [172]. In order to accomplish the desired goal, an eight-step procedure has to be meticulously implemented. The first step consists in the preparation and planning step, which enables the inclusion of future automation aspects in the current analysis. Afterwards the identification of on-site processes and documentation of the related procedural flow occurs. Each working area is scrutinized with the intent to determine primary and secondary task as well as current level of automation. At this point the required minimum and maximum degree of automation can be assessed and analyzed with the purpose of ascertaining a tailored automation strategy [173].

3.2.9.23 Education 4.0

Education 4.0 is an education profile that arises from the novel developments associate with the latest industrial revolution [174]. While the third stage of the educational level, denominated as Education 3.0, emphasizes aspects strictly belonging to the digitalization, the further stage tries to englobe the newest industrial developments that circle around CPS, IoT as well as related phenomena such as Big Data. According to Demartini and Benussi, Industry 4.0 will not only affect the themes treated in several educational paths, but also the associated attributes including learning process and organization [175]. The last named will experience a passage from the real to the virtual sphere, in the sense that online-portals will replace traditional institutional affiliations. Focusing on the learning process, the concept of autonomous and adaptive learning will assume a pivotal role.

3.2.9.24 Electricity Fingerprint Analysis Technology

Electricity Fingerprint Analysis Technology (EFAT) refers to a monitoring system of the power consumption and usage circumstances of electrical devices in order to realize possible energy savages [176]. In comparison to traditional power monitoring systems, so-called “Smart Meters”, the presented technology requires the installation of a single sensor on the power distributor. Concretely, the task of the EFAT consists in the estimation of a more frugal implementation of each electronic device by comparing the synthesized current waveform measured on the main line with respect to the waveform database that stores the current waveform. The confrontation helps to detect wastages and to initiate a follow-up phase, in which the root cause is redressed.

3.2.9.25 Enterprise Resource Planning (ERP)

Enterprise Resource Planning (ERP) is specified as “an accounting oriented, relational database based, multi-module but integrated, software system for identifying and planning the resource needs of an enterprise” [177]. ERP functions as a unique operating panel for an industrial entity following the pursue of supporting the management of nearly all daily business operations, encompassing accounting, procurement, project management and manufacturing [178]. The software system consists of three fractions, which are represented by the transactional database, the management dashboard and the software [179]. While the business value of ERP determines its great popularity, the implementation procedure bothers the enterprises and is therefore object of study in the research realm [180].

3.2.9.26 Flexibility Graphs

Flexibility Graphs refer to a novel method developed with the intent to determine flexibility potential in production sequences [181]. By considering the flexibility in terms of routing flexibility that according to ElMaraghy is specified as the “number of feasible routes of all part types/number of part types”, the flexibility graphs method offers the possibility, by combining several elements of the graph theory, to identify procedural portions characterized by a high degree of flexibility [182]. In concrete, after the determination of the critical path, which is perceived as the sequence devoid of flexibility, the process equipped with a higher grade of freedom is conceptualized in order to optimize the procedural flow associated to the analyzed path. The method exploits also visualization tools, such as a planar graph to intuitively present the determined solution proposal [181].

3.2.9.27 Global Footprint Design

Global Footprint Design is specified as “an integrated heuristic approach to measure and evaluate the strategic value of a specific configuration of a production network with respect to the network’s business environment” [183]. Especially within the fourth industrial revolution, the global footprint, which refers to the distribution of production sites and resources belonging to a company, assumes a pivotal role as essential strategical cost factor. The methodology that ensures the creation of an optimized network design consists of four steps, which are represented by “the generation of possible scenarios based on generic algorithms, the development of the migration effort matrix, the clustering of migration steps and the definition of best migration paths for a global footprint” [184].

3.2.9.28 High Resolution Management

High Resolution Management (HRM) is a management discipline that has been triggered by the phenomenon denominated as Internet of Things [165]. This typology of management is centered on the conscious dealing with so-called high-resolution data. While traditional management techniques were used to handle low-resolution data, which basically are human generated data equipped with a poor quality, the arising technological revolution enable the capture of huge masses of precise data [185]. The illustrated shift offers the opportunity to attain higher entrepreneurial quality, efficiency and flexibility. One of the most impressive examples that demonstrates the benefits related to the successful implementation of HRM, is the fleet management system offered by Bosch, which allows to analyze operators driving behavior, single vehicle conditions or the productivity of the whole fleet [186].

3.2.9.29 Holonic Manufacturing Systems

Holonic Manufacturing Systems (HMS) is manufacturing system capable of adjusting and responding to distinct typologies of business-related challenges by simultaneously preserving the control and exploiting harness synergies of the system [187]. The particularity of these fabrication systems is attributable to the functional production units, which are termed as holons. In concrete, these networked agents support the operator in the controlling process by autonomously configuring the required manufacturing setting and adapting the system strategy and structure according to the obstacles that have to be overcome [188]. HMS offers several key advantages in comparison to traditional manufacturing system, which can be summarized as the ability to cope with rapid product evolutions and unforeseeable circumstances [189].

3.2.9.30 Human Robot Collaboration

Human Robot Collaboration dominates the robotic thematic landscape and demonstrates the significance of the human role within the automation environment [190]. As a result, the robotic realm has been revolutionized in the year 2009, when collaborative robots or so-called CoBots has been brought to the market [75]. By contrast with the traditional robot-conception, in which the stand-alone accomplishment of task is central, CoBots physically interact with human operators by sharing one single working area. The success of the mentioned collaborative application is strictly dependent on the integration of intelligence in robotic systems. While robotic structures have dominated the robotic realm for decades, several associated components, such as gripper, currently move in the foreground of research activities [191].

3.2.9.31 Hybrid-Data-on-Tag Approach

Hybrid-Data-on-Tag Approach is an adaptive on-tag data storage concept that takes advantage on the hybrid utilization of two approaches, which are represented by the data-on-network and RFID-approach, following the pursue of maximizing the identification performance [192]. More precisely, data-on-network is grounded on a centralized network, where all the relevant data associated to a produced entity are stored, whilst the RFID-technology follows a decentralized approach by collecting the workpiece data on a dedicated tag requiring an enormous storage investment [193]. In this light, the Hybrid-Data-on-Tag Approach aims at exploiting the low-memory need of the data-on network and the decentralized nature of the RFID-technology by means of an expedient alternating implementation logic. In cases, where decentralization is essential, such as for the identification in self-adapting production lines, RFID is utilized, while in more standardized application, the data-on network approach is implemented, which results in memory capacity conservation [194].

3.2.9.32 Hybrid Supply Chain

Hybrid Supply Chain is a particular chain manifestation that entails beneficial elements of the lean and agile supply chain [195]. In concrete, the lean supply chain puts emphasis on the performance maximization and resource minimization, while the agile supply chain focuses on the adaptability required in mutating circumstances by means of a modular and scalable chain conceptualization. The purpose followed by this particular typology of supply chain is to act as an active interface between the market and industrial environment in order to capture customer requirements by simultaneously maintaining a lean structure capable of delivering a peak and cost-effective scope of service [196]. To ensure the establishment of a hybrid supply chain, the selection procedure of the suppliers has to be centered on low costs, high quality and elevated degree of responsiveness.

3.2.9.33 Integrated Monitoring System

Integrated Monitoring System (IMS) is specified as a monitoring methodology for industrial activities that is firmly based on at least one computational system [197]. All in all, IMS is composed of four steps that entail the surveillance of computer-generated data, the storage of the accumulated data by means of a centralized database, the examination of the goodness of the registered data exploiting comparative algorithms and the notification of potential issues accompanied by appropriate actions to overcome difficulties. In the area characterized by the fourth industrial revolution, the full interconnectivity of IMS is the peculiarity, which has moved the advanced system in the spotlight [198]. Concretely, in an industrial environment, the concept of IMS is of interest in the operations and maintenance department, which keeps an eye on the service provision of the equipment and the quality of the product, as well as the IT-department that emphasizes the security aspect related to the computational network [199].

3.2.9.34 Internet of Things

Internet of Things (IoT) is the paradigm that has initiated an innovative wave of development within the IT-era. These days, the technological advances associated to the embedment of entities or to put it simple, things within the environment, have become part of the modern reality [38]. The phenomenon affects several technologies or systems, encompassing sensors, actuators, radio frequency technology (RFID), smartphones or CPS that have to be interrelated by means of predetermined patterns following the pursue to achieve consolidated aims [39]. The content of the presented statement can be underpinned through the specification supplied by the International Telecommunication Union (ITU) in the recommendation ITU-T Y.2060, in which IoT is synthetized "as a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [40].

3.2.9.35 ISO-IEC Architecture

ISO-IEC Architecture refers to a CPS-architecture, which has been conceived by the ISO organization [26]. In a first instance, the institution has followed the intent to develop a guideline for the IoT paradigm that in a second moment has been adapted to the CPS-concept. According to Sánchez, Alcarria, de Rivera and Sánchez-Picot, the proposal, which is characterized by an elevated degree of conceptuality, puts enhanced emphasis on two aspect, namely the virtualization and the service-based approach [158]. It is important to note that the illustrated CPS-architecture does not possess an information exchange unit, which is perceived as one of the most relevant downside in light of an Industry 4.0 perspective.

3.2.9.36 Large Scale Machine Coordination Systems

Large Scale Machine Coordination Systems (LSMCS) empowers a flexible manufacturing system composed of oversize-format machines to synergistically dovetail operations with the overall objective to fulfill specific functions [200]. The synergy is grounded on an iterative three-tiered closed loop that entails the unreserved receipt of environmental data gathered by means of sensors, the elaboration of data and the implementation of a particular action, which relies on the computational results. The manifestation of the output occurs in form of mutated machinery states and delivered notification to interrelated machinery units. In order to control the presented loop, two subsequent grades are required, which respectively encompass the deliberative and the metalevel [201]. Key benefit resulting from the adoption of LSMCS is retrievable in an enhance large-scale fleet productivity.

3.2.9.37 Lean Automation

Lean Automation refers to the conceptual amalgamation of automation technologies with the Lean Production paradigm [202]. Even if the term has been put forth around the year 1990, the advances evoked by the fourth industrial revolution caused its new thematic conflagration [203]. Several concepts and technologies attach smartness to traditional industrial entities, such as operators, products as well as machines. The novel figure of the operator, denominated as smart operator, puts into practice traditional lean concept including Andon or one-piece flow exploiting innovative technologies encompassing smart watches and augmented reality. The concept of smart product is differentiable to the traditional productive output by means of the information collection, which occurs among the entire lifecycle. Conclusively, passing over to the smart machinery, the CPSs revolutionize the common understanding associated to machinery-equipment [204].

3.2.9.38 Line Information System Architecture

Line Information System Architecture (LISA) is an event-driven architecture equipped with prototypic information models and grounded on a transformation service, which enables the harmonious cohabitation of loose coupling, flexibility and amenity associate with the upgrading of antiquarian assets [205]. The main target pursued by the illustrated system architecture consists in facilitating the flexibilization of entrepreneurial integration capability as well as the full exploitation of the value provided by gathered data. LISA tries to accomplish successfully the amalgamation of technological off-the-shelf solutions with internationally recognized standards [205]. The conceivers of LISA have already proven the validity of the system architecture through the implementation in the car building industry.

3.2.9.39 Logistics Mall

Logistics Mall refers to a project fathered by the Fraunhofer Institute, whose aim consists in laying the foundations for the creation of an open-access cloud on which IT-logistic services or processes can be leased or purchased [206]. The origination of the virtual shopping mall acts as central solution hub for logistical concerns by offering qualitative and tailored support. The connective power of the logistics mall, which allows to establish an immediate relation between service supplier and users, enables the performance of intensive cost reductions by purchasing exclusively IT-services or products that are strictly necessary. To sum up, scalability, security and transparency constitute the key benefits of the presented virtual mall [207].

3.2.9.40 Manufacturing Execution Systems

Manufacturing Execution Systems (MES) is defined as "a computerized system used in real time documenting, controlling, and management of an entire manufacturing process that includes machines, personnel and support services" [208]. By fulfilling a linking function between the upper planning-stage, represented by the business planning system, and the lowest controlling-level, whose operability depends on the process control system, MES closes the circle that brings into being an integrated automation system [209]. The illustrated system has begun to assume a key role in the business era characterized by the globalization. Notably, MES will enjoy an even higher degree of attention during the latest industrial revolution. Changes provoked by Industry 4.0, which are mainly grounded on four pillars, namely vertical integration, decentralization, connectivity and mobile as well as cloud computing and advanced analysis, will profoundly affect the structure and functionalities associated with the presented system [210].

3.2.9.41 Multi Agent System

Multi Agent System (MAS) refers to the affiliation of a predetermined number of entities denominated as agent, which are governed by specific behavioral schemes [211]. The illustrated system forms a sub-area that is attributable to the artificial intelligence realm. While the proliferation of MAS has reached the peak in several scientific disciplines, the industry still records a growing tendency. The Industry 4.0 phenomenon raises vehemently the issues related to MAS, which has assumed great relevance in several entrepreneurial disciplines, such as planning, scheduling, assembly, control as well as supply chain management [212]. To face the challenges associated with the industrial complexity, traditional control structures have to be urgently replaced with intelligent and autonomous agents [213].

3.2.9.42 Networked CPS Architecture

Networked CPS Architecture is a CPS architecture proposal that focuses on longstanding concepts related to distributed systems [214]. The system architecture is composed of three layers. The initial plane, denominated as physical layer comprises the elements, such as the profiles and protocols that enable the usability for the operator. Passing over to the second plane, which is represented by the service layer, it can be stated that its function consists in translating the physical and application level signals in protocol-conform control signals. The last plan, namely the application layer, aims at providing the request service based on the input supplied by the service level [214]. According to Sánchez, Alcarria, de Rivera and Sánchez-Picot, the proposed CPS architecture has some difficulties to cope with CPS and its features due to its distributed nature [158].

3.2.9.43 NIST-Architecture

NIST-Architecture refers to a CPS-model framework evolved by NIST. The followed pursue is to place at disposal a globally accepted fundament for the conceptualization and technical realization of CPS independently from system engineering procedures [23]. The proposed architecture that according to Sánchez, Alcarria, de Rivera and Sánchez-Picot is able to fulfill the requirements emerged from the Industry 4.0 phenomenon, is based on three basic layers, which are respectively represented by the lowest-level control plane, the highest-level business process management plane and finally the data analytics plan [158]. The high approval rate of the NIST-architecture is determined by the decoupling of the data analytics layer with the control- and business process management plane, which results in beneficial effects especially during the utilization phase, and the presence of an apparent connecting point for devices [215].

3.2.9.44 Object Fingerprint Technology

Object Fingerprint Technology is a technological application that enables the recognition and authentication of produced units by means of subtle structural patterns that characterize the surface finish of a product [216]. The unique pattern, which equals the fingermark of humans, are determinable exclusively through the deployment of a dedicated technology, which unlike the human-eye or regular camera, is capable of distinguishing the characteristic surface finish. The presented technology is perceived as one of the most efficient anti-counterfeiting measure that tackles the diffused phenomenon of falsification [216]. A prominent instance for the implementation of the object fingerprint technology is represented by the US- baby carrier brand Dadway.

3.2.9.45 Object Self-Service

Object Self-Service refers to a concept that enables machines to accomplish the reorder procedure autonomously [165]. In the presented conceptual approach, which finds application in a wide-range of industrial environments, due to its universal practicability to processing devices that are in need of continuous and demand-oriented provision of material, the support of human operators is not of interest. The logic behind the object self-service is firmly grounded on algorithms entailed in the economic order quantity (EOQ) model, which constitutes an essential part of the procurement logic [217]. In order to prove the practical feasibility of the illustrated concept, Amazon has brought into being a project, denominated as "amazon dash replenishment service", which allows household appliances to reorder autonomously needed means [218].

3.2.9.46 Open Innovation Models

Open Innovation Model expresses a business model that bursts traditional enterprise boundaries associated with the innovation process by allowing entities appertaining to the surrounding environment to actively shape the strength of a company [219]. The presented model can appear in several forms, including virtual platforms, idea contests as well as innovation-centered networks [220]. Even if the model of open innovation is strictly related to convincing benefits, such as the cost-reduction, enhanced innovation potential and synergism, several downsides deter enterprises to put into practice this business model. Among the most significant aspects, the revealing of innovative concepts, the forfeiture of the decisive competitive advantage as well as the enhancement of the complexity belonging to the delicate innovation process, have to be highlighted [221].

3.2.9.47 Personalized Customization Manufacturing System

Personalized Customization Manufacturing System (PCMS) refers to an individually appointed manufacturing system, whose peculiarity consists in the supply of mobile services [222]. Grounded on a cutting-edge cloud platform, which assumes the function of an information processing instrument, PCMS entails an adaptable production mechanism that enables the optimization of the entire production procedure as well as the personalization of orders. In this light, two beneficiaries can be pointed out. First of all, the customer, whose requirements are totally fulfilled through the customizability, and secondly the enterprise that exploits the advantages of the performed optimization management [223]. Concretely, PCMS consists of four key technological elements that are respectively "the collaborative technology of manufacturing entity, network resources information processing technology, cloud data processing technology as well as the client terminal application development" [222].

3.2.9.48 Physical Freemium

Physical Freemium is a byword for a business model, in which a physical entity is offered in conjunction with a free of charge virtual service [165]. The business strategy behind the convincing package, which consists of physical and virtual elements, targets the enhancement of the subjective value perception attributable to the product and the privileged market placement in the premium product segments [224]. In addition, the provided virtual service is characterized by an elevated degree of basicity, which in turn offers the opportunity to sell upgraded virtual service delivery. Typical instances are the extendable remote-control option as well as the digital maintenance service [165].

3.2.9.49 Physical Internet

Physical Internet refers to a theoretical construct that aims at transposing the conceptual characteristics and functioning related to the traditional internet to logistics [225]. The key element around which the physical internet rotates is epitomized by the interconnectivity of logistical entities. The illustrated characteristics is realized by means of information technology, modular load units and interfaces as well as protocols and procedures, which enable respectively the persistence of digital, physical and operative interconnectivity [226]. The illustrated three pillars form the fundament for a universal and interconnected logistic network, which is intensively reminiscent of the traditional internet, whose object consists in the large-scale sharing of digital data by interconnecting computational devices [227].

3.2.9.50 Plug and Produce Approach

Plug and Produce Approach expresses a technological concept, which implies a high and easy adaptability of manufacturing systems [188]. According to novel business requirements or scenarios, the production system can be assembled from pluggable production entities bypassing configurational issues [228]. The integrability of the plug-in entities enables the immediate initiation of the production process. To assure the adaptability belonging to the production system, pluggable entities have to possess three fundamental properties, which are respectively represented by the integrability, the modifiability and the extractability with respect to the production system. The illustrated properties have to be in effect for the physical as well as for the digital dimension [229].

3.2.9.51 Product as a Point of Sales

Product as a Point of Sales is a business model that empowers physically produced units to transact additional business processes, such digital sales or marketing [165]. The illustrates service can be realized exclusively by means of a computational device. For getting more concrete, an already implemented application is depicted as an instance. The exploitation of the functionalities of a smartphone can give direct access to the e-commerce platform of an enterprise, simply by pointing the device at a produced unit. The generated data can be utilized by the company to initiate effective marketing activities. As a result, proper advertising as well as cross selling can be realized [165].

3.2.9.52 Product Lifecycle Management

Product Lifecycle Management (PLM) refers to a methodical procedure that aims at accompanying the evolution of a produced unit over its entire cycle time, commencing with the development up to the decline [230]. The discipline, which enjoys greatest appreciations in variegated industrial environments, has been established as pillar of the current product management by enabling synergies between processes, data, systems as well as human activities [231]. By tracking the stages undergone by a product, an antidote to enhancing business complexity is created. The most notable advantages attributable to the implementation of PLM are represented by reduced costs and time to market as well as improved product quality and functional reliability [232].

3.2.9.53 Product-Service Architecture

Product-Service Architecture (PSA) illustrates a novel conceptual architecture, which grounded on a cloud system facilitates the harmonic arrangement of decentralized product or service generation [233]. The objective followed by the presented architecture consists in offering a theory-oriented guideline for the realization of value-creation plans, which rotate around production or service provision. Central elements for the implementation of PSA are the production units and the final consumer that are interrelated by courtesy of the architecture [234]. The fundamental elements that compose PSA are represented by the service user interface, the intention prediction module, the value co-creation satisfaction level module, the service planner module, the workflow management system as well as the protocol management system [235].

3.2.9.54 Radio-Frequency Identification (RFID)

Radio-Frequency Identification (RFID) exploits the properties of electromagnetic fields with the purpose of tracking and recognizing tags adhered to entities of interest [236]. In order to accomplish successfully the identification process two crucial elements, have to be deployed, namely the readers and the tags, which can be either passive or active. Active entities differ from passive ones in that they are capable of emitting signals. In practice, at least one of the RFID-instruments have to possess active properties. However, the heart of the technology is definitely represented by the tags, which according to the configured frequency band, store data in form of electronic product code (EPC) [237]. The implementation range of the technology has successfully crossed the borders of industry a long time ago, assuming an essential role in variegated areas, such as the retail trade, the rental library and the animals identification [238].

3.2.9.55 RAPID Machine Learning

RAPID Machine Learning refers to a sub-discipline of artificial intelligence that enables computational devices to take lessons by means of acquired data [197]. The conceptual approach, which differs substantially from the traditional machine learning concepts based on semi- or fully-supervised learning, allows the machine to autonomously and instantaneously pick up issues and share the learning experience with the networked machinery fleet. Besides human-recognizable defects, RAPID machine learning puts emphasis on the silent fault detection of errors in order to guarantee the perfect functioning of the machine [239]. The high accuracy in the fault detection is realizable exclusively by implementing a highly qualitative sensor equipment, whose delivered data are evaluated by means of a particular interpretation procedure [240].

3.2.9.56 Reference Architectural Model Industry 4.0 (RAMI 4.0)

Reference Architectural Model Industry 4.0 (RAMI 4.0) illustrates a framework, whose objective comprises the creation of a collective understanding of Industry 4.0 by conceptually categorizing innovative technologies and concepts [241]. By means of a three-dimensional coordinate system, RAMI 4.0 offers the possibility of integrating distinct viewpoint associated to technological aspects of the fourth industrial revolution [242]. The three axes are respectively represented by the hierarchy levels, the life cycle and value stream. While the first axis reflects the hierarchical stages entailed in the international standard IEC 62264, the second axis emphasizes the lifecycle-related elements according to the international standard IEC 62890. The unique vertical axis, which consists of six layers, focuses on the properties of a machine [241].

3.2.9.57 Remote Usage and Condition Monitoring

Remote Usage and Condition Monitoring is a business model element centered on the utilization surveillance of smart production entities [165]. In particular, the capturing of data in real-time, which serves as essential basis for performing further analysis, is able to depict the performance or negative influences deriving from the industrial environment. The implementation of the remote surveillance instrument enables enterprises to respond proactively to upcoming concerns and to adopt efficiently preventive maintenance measures [165]. Remote Usage and Condition Monitoring is put into practice by means of smart machines, which are equipped with sensor equipment, and a specific monitoring software that acts as interface between operator and machine. The business model component has been already successfully implemented by Konecranes, a Finnish crane and lifting equipment producer that assumed the global leadership role in the sector [243].

3.2.9.58 Science Fiction Prototyping

Science Fiction Prototyping (SFP) is a byword for an intelligent environment research tool, which enables forecasting practice grounded on science fiction [244]. The immersion in a futuristic environment, which can occur by means of variegated technologies, above all virtual reality, stimulates the creative streak of researcher. The support in the product innovation has been already implemented by several well-known enterprises, such as Intel and UX design [245]. In order to put into practice the SFP-method, a five-step procedure has to be followed. Firstly, the technological mean, through which the futuristic environment is realized, has to be chosen. Within the forward-looking framework, relevant temporal milestones, which strongly affect consumer habits, have to be pointed out. Based on the assumption, several possible scenarios are established, which could determinately be accountable for the conformation of the prototype. Conclusively, the properties of the prototype are determined [246].

3.2.9.59 Self-Learning Anomaly Detection Technology

Self-Learning Anomaly Detection Technology refers to a technology, whose scope consist in the safeguarding of computational devices from variegated typologies of cyberattacks [197]. The novelty proposed by this protection technology consists in the self-learning property that allows to deliver hazardous warnings [247]. In concrete, the characteristic is strongly dependent on a learning module, which is continuously updated. Self-Learning Anomaly Detection Technology utilizes a combination of two modules, denominated as feature extractor and anomaly detector, whose application results in the identification of potential issues that are shared with the entire network, in which the entrepreneurial technology is embedded. The last-mentioned module, namely the anomaly detector is grounded on a combination of variegated data mining techniques [248].

3.2.9.60 Smart Behavioral Filter

Smart Behavioral Filter (SBF) is a safety feature that follows the pursue to ensure the protection of PLCs [249]. The defense against so-called logic attacks, which are considered as a sequence of well-developed digital bundles, prevents the PLC from adopting randomized an unforeseeable behavior pattern. In concrete, the duty of the SBF consists in the recognition of hazardous occurrences and in the isolation of the affected PLC to avoid the infection of the entire computational system, which is responsible for the surveillance of the manufacturing system. SBF facilitates the detection of intruder through the release of a precise alarm [250].

3.2.9.61 Smart Process Manufacturing

Smart Process Manufacturing refers to a technological concept that exploits the rugged performance of information technology to ensure the persistence of an effective information exchange and a self-adaptive capability [251]. The uppermost maxim followed by smart process manufacturing is represented by the minimization of final project rejection. In this light, each process involved in the manufacturing is equipped with so-called linking process entities, whose area of responsibility encompasses the execution of sequential inline product units control [252]. In case of recognizing anomalies, the linking process entity immediately generates an alert. The prompt notification allows to minimize the time dedicated to the autonomous search of the root cause by simultaneously keeping the manufacturing defects within the limits. Especially in sector that require highest process reliability smart process manufacturing is of interest [253].

3.2.9.62 Smart Shopfloor Architecture

Smart Shopfloor Architecture acts as a reference model for enabling the dynamic scheduling and rescheduling of the entire shopfloor [254]. The presented architecture comprises three layers, which are respectively the physical layer, the logical layer and the communication layer. Commencing with the physical layer, it can be stated that this portion of the model is responsible for the real accomplishment of task [212]. Each entity of the shopfloor capable of executing transportation and processing processes, such as manufacturing cells as well as automated guided vehicles, belongs to the illustrated layer. The logical layer manages the procedural behavior of each device, which is perceived as autonomous but embedded element of the smart shopfloor, by means of scheduled operations. Conclusively, the communication layer sets up the interaction between physical and logical layer, which are capable of sending and receiving notifications [255].

3.2.9.63 Structure Dynamic Control Mechanism

Structure Dynamic Control Mechanism constitutes the fundament of a service-oriented model that aims at enabling the dynamic scheduling of a flexible job shop [58]. The primary goal is represented by the establishment of a continuous flow within an Industry 4.0-conform productive environment composed of uniform and autonomous machines. The novelty of the illustrated mechanisms consists in the synchronized surveillance of operations and discrete assignments that is put into practice by adopting an innovative scheduling approach, which dynamically interprets the performed activities and chronologically disjoints the current scheduling issues. The expressly developed algorithms is grounded on a mathematical construct, denominated as the continuous maximum principle [157].

3.2.9.64 System Invariant Analysis Technology

System Invariant Analysis Technology (SIAT) is categorizable as a machine learning technology, whose functionality consists in the evaluation of coherent time series sequences grounded on collected sensor measurement data [197]. The relationship among the data is compared with predefined numeric patterns, which are synonymous for a usual behavior model. In cases of discrepancies characterized by anomalous numeric relationships, the model reveals the unconformity in the system operation. SIAT is marked by a great adaptability to variegated applications due to its analytical procedure based on time series of numeric values [256]. A popular application field is constituted by the system management of productive processes. In contrast to conventional analytical technologies, SIAT is capable of identifying silent faults, such as progressive machine performance retrenchments not recorded by means of traditional leading indicators [257].

3.2.9.65 Tele-Maintenance

Tele-Maintenance refers to a particular typology of industrial maintenance, whose peculiarity consists in the remoteness. Despite the remote servicing of the machinery fleet, which has already struck a significant chord within industrial environments, the novelties related to Industry 4.0 tele-maintenance incorporate technologies that have assumed an essential role within the fourth industrial revolution, namely AR and VR [258]. The listed technologies can be related to the tele-maintenance process in a distinct way. Commencing with AR, tele-maintenance is realizable by means of a human operator or technician that is centrally guided by a servicing expert through an AR-device [259]. Passing over to VR, tele-maintenance is performed at first in a virtual replication of the real industrial environment. The applied operations can be transferred by courtesy of IT-technologies to the machinery fleet [260].

3.2.9.66 Virtual Commissioning

Virtual Commissioning (VC) is defined as a universal and multidisciplinary methodology centered on simulation models, which aims at examining the goodness of a control logic [261]. In concrete, the illustrated concept involves emulating the behavior of mechatronic systems by means of dedicated software. The mutation of the design generated through the software allows to deploy a PLC logic that is characterized by optimized behavior. The design procedure is composed of four substantial passages that are respectively represented by the process planning, the physical device modeling, the logic device modeling as well as the system control modeling [262]. Provided the applicational success of the methodology, virtual commissioning has been able to burst the industrial borders and reach variegated realms, like the educational one [263].

3.2.9.67 Virtual Engineering Object

Virtual Engineering Object (VEO) refers to a concept centered on a self-perpetuating representation of an engineering object that is able to acquire, save, share and ameliorate information by means of accumulated experience [264]. The encapsulation of knowledge is grounded on three basic elements that are respectively represented by the inclusion of the decisional pattern influenced by the collection of experience, the spatial representation as well as the correlation of the virtual entity with the physical engineering object [265]. In order to realize an object-oriented knowledge base, at least one of six specified characteristic, including "characteristics, functionality, requirements, connections, present state and experience, have to fit with the gathered data" [113]. Uppermost objective of VEO is to provide the framework conditions that facilitate the provision of a sophisticated engineering object.

3.2.9.68 Virtual Engineering Process

Virtual Engineering Process (VEP) is a byword for a self-perpetuating representation of production or assembling procedural plans, which encompass the information spectrum of the involved shop floor levels [113]. In particular, the nature of the operation, the scheduling composition as well as the eligible resources for the proper realization are of interest. VEP possesses a design, which is decomposable into three modular entities, namely operations, resources and experience [265]. As the terminology implies, operations put emphasis on several parameter related to the operational implementation, such as the scheduling or procedural instructions. Passing over to the second module, the resources utilized to realize the artefact take the center stage. Special attention is placed on machinery and auxiliary devices. Conclusively the experience is illustrated, which focuses on the acquisition of knowledge with strong decisional character [264].

3.2.9.69 Virtual Enterprise

Virtual Enterprise (VE) refers to a computerized and networked cooperation of flexible SMEs that place at disposal particular competences or resources with the purpose of exploiting the potential provided by novel business opportunities [266]. In contrast to traditional alliances, VE emphasizes the relevance of two characteristics, which are represented by the information technology as well as the dynamic nature of the established partnership [267]. The presented peculiarities substitute outdated technologies as well as restrictive pre-defined contracts limiting the scope of action of involved enterprises, which are not capable of generating fully valuable synergies. VE undergoes several organizational life cycle stages, which are represented by the establishment, the operative activity, the dynamic evolution and finally the decline [268].

3.2.9.70 Virtual Reality

Virtual Reality (VR) is specified as "the term used to describe a three-dimensional, computer generated environment which can be explored and interacted with by a person. That person becomes part of this virtual world or is immersed within this environment and whilst there, is able to manipulate objects or perform a series of actions" [89]. In comparison to AR, which puts emphasis on ameliorating the reality by means of digital entities, VR focuses on the "inclusion of the user in a completely virtual environment" [269]. This characteristic feature is contemplated as the key concept attributable to the technology, which can be put into practice through the implementation of headsets, monitors, workbenches, walls or caves [270].

3.2.9.71 Virtual Training

Virtual Training (VT) refers to a formation methodology, which grounded on VR-technologies reproduces realistic environments in order to maximize the learning effect of the instructed personnel [271]. Besides numerous applications, the implementation spectrum comprises also the industrial realm, which benefits particularly from the illustrated training form. Indeed, the exploitation of a virtual environment allows the instructor to simulate several scenarios and to demonstrate the effect of defective operative behavior. In addition, training focused on the execution of hazardous operations that involve particular substance or machines are perfectly simulated in a virtual environment without risking to provoke grievous body harms [272]. According to Hoedt et al., VT allows to enhance the quality of the learning process by 22% in comparison to traditional training forms [273].

3.2.9.72 Visual Analytics

Visual Analytics is perceived as a scientific discipline, which provides aid in the "analytical interpretation of large-scale data sets by means of interactive visual user interfaces" [274]. By incorporating several peculiarities attributable to a wide range of scientific realms, such as computational science, design and social disciplines, visual analytics is capable of placing at disposal a valuable tool for managing outrageous intricated issues. The emphasis of the visual analytics instrument relies on four major pillars, which are respectively represented by analytical reason techniques, data illustration and modification, result-oriented communication techniques as well as visual illustration and interaction techniques [275]. In an industrial era, in which industrial entities are inundated by a flood of data, analytical instruments, such as visual analytics tool, assume a pivotal role [276].

3.2.9.73 Volume Cycle

Volume Cycle refers to a novel program planning instrument, which faces the problems associated with the scheduling of the JIS component supply in decentralized production control logics [181]. Traditional program planning patterns have demonstrated to be too rigid to cope with the dynamins of decentralized control structures. The concept is grounded on the provision of an established time window within the production schedule, in which a predetermined production orders have to be allocated. The flexibility compared to traditional production plans, like the pearl chain concept, is epitomized by the absence of a rigid sequential specification. Indeed, as suggested by the terminology of the instrument, the emphasis is placed on the volumes and the finalization of predefined production order [181].

3.2.9.74 Wireless Sensor Network

Wireless Sensor Network (WSN) is a byword for an interconnected system composed of spatially dispersed sensor devices that follow the objective of surveilling the condition of physical entities as well as transferring the gathered data to a predefined information hub [277]. The basic elements composing the network are denominated as sensor nodes and classified according to the frequency, the data rate, the range as well as the network typology [278]. WSN, which finds application in an extended range of realms, including body area, urbanistic and infrastructure, industry and agriculture, military and crime prevention as well as environment, assumes a pivotal role, especially in an era characterized by the fourth industrial revolution [279].

3.2.9.75 Workload Management Systems

Workload Management System (WMS) refers to a concept, whose objective relies on ensuring optimal operating conditions of computational entities within physical, virtual or cloud-environments. The presented managerial paradigm is centered on the dynamic allocation of digital work-packages [280]. Uppermost maxim is represented by the achievement of a maximal utilization rate by simultaneously guaranteeing a high degree of reliability as well as an elevated operational security. WMS synergistically encompasses selected subdivisions of IT-disciplines, such as the management of computational systems, the visualization of performance as well as the development of software-applications. In industrial environments influenced by the Industry 4.0 phenomenon, the managerial practice has struck a significant chord [281].

3.3 Conclusion of the third chapter

The third section of the master thesis puts emphasis on the research methodology and approach. The core part of the illustrated chapter consists in the conduction of the systematic literature review, whose purpose is epitomized by the provision of a solid methodical base to the entire academic elaboration. After a brief scrutinization of the record collection, which allows to gather additional information such as the frequency of key words or the hottest thematical research focus associated to Industry 4.0, the essential content analysis has been initialized. The evaluation allows to individuate a valuable set of Industry 4.0 elements. Actually, a total of 75 Industry 4.0 elements has been identified, categorized and conclusively described. The accomplishment of the listed passages and the definition of dimensions and categories of Industry 4.0 elements, enable the creation of the fundaments for the conceptualization of the Industry 4.0 assessment tool.

Chapter 4

CONCEPT OF AN ASSESSMENT TOOL FOR INDUSTRY 4.0 IMPLEMENTATION

The core part of the entire master thesis is entailed in the fourth chapter. Factually, the development of a deployable assessment tool for Industry 4.0 implementation is executed grounded on a step by step procedure. Commencing with the previously exposed Industry 4.0 elements, the determination of straightforward concepts is executed. With regard to the introduced Industry 4.0 concepts, specific maturity levels, which consists of five distinct stages, are established. While the concepts and maturity levels form the content-related framework of the assessment tool, the specification of the quantitative assessment approach delineates the calculation scheme. In order to enhance the ease of use of the assessment tool, the capability of visualization tools including graphs and diagrams is exploited. The last conceptional section of the assessment tool entails the ranking of Industry 4.0 concepts, whose accomplishment allows the enterprise to match the aspired Industry 4.0 standards. Conclusively, the realized excel-based assessment tool is presented.

4.1 Definition of the evaluable Industry 4.0 concepts

The initial sub-chapter puts emphasis on the determination of Industry 4.0 concepts, which shape the content conformation of the assessment model. Based on the generalization of the results established by courtesy of the systematic literature review, which enables the identification of 75 Industry 4.0 elements, a consistent portion of the conceptual collection has been determined. The reason for the adopted approach lies in the fact that the individuated Industry 4.0 elements, in most of the cases, are characterized by a subject-specific nature, which is perceived as a complicating factor in regard to the assessment perspective. The 75 Industry 4.0 elements are condensed in order to achieve a reduced number corresponding to 40 concepts. The comprehensive summary, which facilitates the recognition of associations between elements and concepts, is presented in tabular form as follows by means of Table 6.

Nr.	Industry 4.0 Elements	Industry 4.0 Concepts
1	Additive Manufacturing (3D-Printing)	Additive Manufacturing (3D-Printing)
2	Large Scale Machine Coordination Systems (LMCS)	Agile Manufacturing System
3	Personalized Customization Manufacturing System (PCMS)	
4	Smart Process Manufacturing (SPM)	Smart Assistance Systems
5	Artificial Intelligence (AI)	Artificial Intelligence
6	RAPID Machine Learning (RML)	
7	Self-Learning Anomaly Detection	

	Technology	
8	Lean Automation	Automated Manufacturing & Assembly
9	Automated-Storage-and-Retrieval-System (ASRS)	Automated Storage Systems
10	Autonomous Guided Vehicles (AGV)	
11	System Invariant Analysis Technology (SIAT)	Big Data Analytics
12	Workload Management Systems (WMS)	Cloud Computing
13	Cloud Computing (CC)	
14	Virtual Enterprise (VE)	Collaboration Network Models
15	HRC (Human Robot Collaboration)	Collaborative Robotics
16	7Epsilon	Continuous and Uninterrupted Material Flow Models
17	Smart Shop Floor Architecture	
18	Continuous Flow Flexible Job Shop (CF-FJS)	
19	ISO-IEC Architecture	CPS Standards
20	Line Information System Architecture (LISA)	
21	NIST Architecture	
22	5C Architecture	
23	CPS Architecture Model	
24	Networked CPS Architecture	
25	Reference Architectural Model (RAMI 4.0)	
26	Cybersecurity (CS)	Cyber Security
27	Smart Behavioral Filter (SBF)	
28	Dynamo (Dynamic Levels of Automation for Robust Manufacturing Systems)	Decision Support Systems

29	Digital Add-on	Digital Add-on or Upgrade
30	Wireless Sensor Network (WSN)	Digital and connected workstations
31	Digital Lock-in	Digital Lock-In
32	Product as a Point of Sales	Digital Point of Sales
33	Product-Service Architecture (PSA)	Digital Product-Service Systems
34	E-Kanban	E-Kanban
35	Enterprise Resource Planning (ERP)	ERP / MES Integration
36	Manufacturing Execution Systems (MES)	
37	Physical Freemium	Freemium
38	Hybrid-Data-on-Tag Approach	Identification and Tracking Technology
39	Object Fingerprint Technology	
40	Radio-frequency identification (RFID)	
41	Autonomous Production Control (APC)	Integrated and Digital Real-Time Monitoring Systems
42	Integrated Monitoring System	
43	Visual Analytics System	
44	Electricity Fingerprint Analysis Technology	
45	Cyber-Physical Systems (CPS)	Internet of Things and Cyber-Physical Systems
46	Internet of Things (IoT)	
47	Object Self Service	Object Self Service
48	Open Innovation Models	Open Innovation
49	Computer Aided Design (CAD)	PDM and PLM
50	Computer Aided Engineering (CAE)	
51	Computer Aided Manufacturing (CAM)	

52	Digital Twin	
53	Product Lifecycle Management (PLM)	
54	Virtual Engineering Objects (VEO)	
55	Virtual Engineering Process (VEP)	
56	Plug and Produce Approach	Plug and Produce
57	Remote Usage and Condition Monitoring	Remote Monitoring of Products
58	High Resolution Management	Role of the Operator
59	Flexibility Graphs	Self-Adapting Manufacturing Systems
60	Structure Dynamic Control (SDC) Mechanism	
61	Volume Cycle	
62	Holonic Manufacturing Systems (HMS)	
63	Multi Agent System (MAS)	
64	Artificial Self-Organizing systems (ASO)	
65	Logistic Mall	Servitization and Sharing Economy
66	Science Fiction Prototyping (SFP)	Simulation
67	Virtual Commissioning (VC)	
68	Global Footprint Design	Sustainable Supply Chain Design
69	Hybrid Supply Chain	
70	Physical Internet (PI)	
71	Telemaintenance	Tele- and Predictive Maintenance
72	Education 4.0	Training 4.0
73	Augmented Reality (AR)	VR and AR
74	Virtual Reality (VR)	
75	Virtual Training	

Table 6: Industry 4.0 concepts obtained by means of the generalization of Industry 4.0 elements.

The obtained results clearly evidence the technological, operational, organizational as well as socio-cultural nature of the concepts. While the technological and operational concepts, which assume a predominate role within the assessment model, distinguish themselves by completeness, the organizational and socio-cultural conceptualization are characterized by a slight lack of substance. In respect thereof, two additional Industry 4.0 concepts has been enclosed with the intent to bridge the gap. With regard to the socio-cultural conceptualization, the cultural transformation provoked by the fourth industrial revolution has been added, whilst the concept belonging to the organizational sphere is denominated as Industry 4.0 roadmap, which focuses on the determination of a straightforward and concrete Industry 4.0 implementation plan [1].

Finally, a total of 42 Industry 4.0 concepts, which delineate the thematic focus of the assessment model, has been established. The wide range of covered subject matters enquires about the introduction of a transparent structural framework. In this light, the determination of two distinct level dimensions has been executed. Commencing with the second level dimension that is levelly closer to the singular concepts, a total of 21 categorization units have been identified. Table 7 depicts comprehensively and in alphabetical order the established units of the second level dimension.

II. Level Dimension
Agile Manufacturing Systems
Monitoring & Decision Systems
Big Data
Production Planning and Control
Business Models 4.0
Innovation strategy
Strategy 4.0
Supply Chain Management 4.0
Human Resource 4.0
Work 4.0
Culture 4.0
Communication & Connectivity
Cyber Security
Deep Learning, Machine Learning, Artificial Intelligence
Identification and Tracking Technology

Additive Manufacturing
Maintenance
Robotics & Automation
Product Design and Development
Standards 4.0
Virtual Reality, Augmented Reality and Simulation

Table 7: Second level dimension of Industry 4.0 concepts.

The final step, whose accomplishment ensures the presence of an exhaustive structural categorization, consists in the specification of the highest-level dimension. The so-called first level dimension, which is composed of four units, reflects the nature of the conceptual collection. The list of first level dimension units is presented in Table 8 as follows:

I. Level Dimension
Operation
Organization
Socio-Culture
Technology

Table 8: First level dimension of Industry 4.0 concepts.

The detailed explanation associated to the systematic categorization of the established conceptualization, enables the illustration of the comprehensive table, whose content entails the Industry 4.0 concepts in connection with the first and second level dimension. Table 10 is perceived as an overview of the executed systematic generalization; whose principle scope lies in the representation of the categorized Industry 4.0 concepts.

Nr.	I. Level Dimension	II. Level Dimension	Industry 4.0 Concept
1	Operation	Agile Manufacturing Systems	Agile Manufacturing System
2	Operation	Agile Manufacturing Systems	Self-Adapting Manufacturing Systems
3	Operation	Agile Manufacturing Systems	Continuous and Uninterrupted Material Flow Models

4	Operation	Agile Manufacturing Systems	Plug and Produce
5	Operation	Monitoring & Decision Systems	Decision Support Systems
6	Operation	Monitoring & Decision Systems	Integrated and Digital Real-Time Monitoring Systems
7	Operation	Monitoring & Decision Systems	Remote Monitoring of Products
8	Operation	Big Data	Big Data Analytics
9	Operation	Production Planning and Control	ERP / MES Integration
10	Organization	Business Models 4.0	Digital Product-Service Systems
11	Organization	Business Models 4.0	Servitization and Sharing Economy
12	Organization	Business Models 4.0	Digital Add-on or Upgrade
13	Organization	Business Models 4.0	Digital Lock-In
14	Organization	Business Models 4.0	Freemium
15	Organization	Business Models 4.0	Digital Point of Sales
16	Organization	Innovation strategy	Open Innovation
17	Organization	Strategy 4.0	Industry 4.0 Roadmap
18	Organization	Supply Chain Management 4.0	Sustainable Supply Chain Design
19	Organization	Supply Chain Management 4.0	Collaboration Network Models
20	Socio-Culture	Human Resource 4.0	Training 4.0
21	Socio-Culture	Work 4.0	Role of the Operator

22	Socio-Culture	Culture 4.0	Cultural Transformation
23	Technology	Big Data	Cloud Computing
24	Technology	Communication & Connectivity	Digital and Connected Workstations
25	Technology	Communication & Connectivity	E-Kanban
26	Technology	Communication & Connectivity	Internet of Things and Cyber-Physical Systems
27	Technology	Cyber Security	Cyber Security
28	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Artificial Intelligence
29	Technology	Deep Learning, Machine Learning, Artificial Intelligence	Object Self Service
30	Technology	Identification and Tracking Technology	Identification and Tracking Technology
31	Technology	Additive Manufacturing	Additive Manufacturing (3D-Printing)
32	Technology	Maintenance	Predictive Maintenance
33	Technology	Maintenance	Tele-Maintenance
34	Technology	Robotics & Automation	Automated Storage Systems
35	Technology	Robotics & Automation	Automated Transport Systems
36	Technology	Robotics & Automation	Automated Manufacturing & Assembly
37	Technology	Robotics & Automation	Collaborative Robotics
38	Technology	Robotics & Automation	Smart Assistance Systems

39	Technology	Product Design and Development	PDM and PLM
40	Technology	Standards 4.0	CPS Standards
41	Technology	Virtual Reality, Augmented Reality and Simulation	VR and AR
42	Technology	Virtual Reality, Augmented Reality and Simulation	Simulation

Table 9: Complete table of categorized Industry 4.0 concepts.

4.2 Definition of maturity levels

The conceptual backbone of the assessment model is finalized with the introduction of the distinct maturity levels that are directly linked to each Industry 4.0 concept. Each stage specifies the peculiarities that the evaluated enterprise possesses or rather desires to achieve in order to comply with the Industry 4.0 requirements.

The factual reason that leads to the specification of exact five maturity levels is retrievable in the literature associated to Industry 4.0 assessment tools. According to the results of the scrutinization of the maturity models, it can be asserted that five stages are outstandingly suitable to map the ripeness in regard to the Industry 4.0 concepts [1], [122].

In contrast to the cited maturity models, which instance a singluar term for each maturity level, the developed assessment model opts for the adoption of a hybrid approach. Indeed, the ambivalent nature of the specification derives from the alternated application of single terms and concise sentences.

While the precise terminology constitutes the preferential solution, in cases characterized by certain ambiguity related to the comprehension of the conceptual maturity, a brief statement as well as an example are integrated. The pursue followed by the selected approach is constitued by the facilitation of the comprehension, which impacts beneficially the assessment execution quality.

The described maturity levels are illustrated in Figure 19 as follows:

Nr.	*I. Level Dimension*	*II. Level Dimension*	*Industry 4.0 concept*	*Maturity Level 1*	*Maturity Level 2*	*Maturity Level 3*	*Maturity Level 4*	*Maturity Level 5*
1	**Operation**	**Agile Manufacturing Systems**	**Agile Manufacturing system**	No flexibility of manufacturing system */system produces only one kind of product with a certain capacity*	Scalable manufacturing system */system is able to de/increase the volume capacity*	Modular and reconfigurable manufacturing system */system is able to be adapted for other products*	Flexible manufacturing system */system is able to produce different variants of a product family*	Agile/changeable manufacturing system */system is designed to be utilized also for new products*

Figure 19: Exemplary representation of Industry 4.0 concepts and maturity levels.

4.3 Quantitative assessment approach

The completion of the comprehensive representation of the theoretical assessment model fraction allows to pass over to the delineation of the calculation procedure. In concrete, the quantitative assessment approach is decomposable into five elements that are respectively represented by the Firm Industry 4.0 Score, the Firm Industry 4.0 Target Score, the Importance for the Assessed Firm, the Firms Gap to Target and conclusively the Weighted Gap.

The *Firm Industry 4.0 Score* is a subjective value provided by the interviewed representative of the enterprise. With the aid of the statement associated to the maturity level, the respondent tries to estimate the degree of Industry 4.0 concerning a particular concept. To guarantee the uniformity and evaluability of the score, a range that commences with one, which is considered to be the lowest level, and ends with five, which is perceived as the highest reachable account, is taken into account.

The *Firm Industry 4.0 Target Score* refers to a subjective value that depicts the level of Industry 4.0 with regard to a concept, which the interviewed representative suggested to be ideal for the own enterprise. Supported by the maturity level statements, the interviewee identifies the level of Industry 4.0 related to a concept that confers a decisive competitive edge to the own company. Also, in this case the range goes from a minimum of one to a maximum of five.

The *Importance for the Assessed Firm* is a subjective value that epitomizes the degree of relevance of the treated Industry 4.0 concept. As a matter of fact, not all the listed concepts possess the identical significance, which massively depends on the sector of interest as well as on the unique operative nature of the enterprise. The importance of the concepts is expressible by courtesy of a scale that starts with one, which typifies the minimum, and finishes with five, which represents the maximum.

The *Firms Gap to Target* specifies the established deficiency that have to be rectified in order to assume a trebly competitive position. The extent of the gap can be ascertained by means of a subtraction. The formula of the straightforward arithmetical operation is presented as follows:

$$\textit{Firm Gap to Target} = \textit{Firm Industry 4.0 Target Score} - \textit{Firm Industry 4.0 Score}$$

The *Weighted Gap* composes the last procedural step of the quantitative assessment approach. The purpose followed by the weighted lacuna is to confer a perception related to the gravity of the Industry 4.0 immaturity. In addition, the presented calculation element functions as a transparent prioritization methodology of the later explained work-packages, whose implementation equalizes the achievement of the desired maturity with regard to a specific concept. The precedence is established through a division. The formula of the arithmetical operation is demonstrated as follows:

$$Weighted\ Gap\text{:}\ \frac{Firm\ Gap\ to\ Target\ *\ Importance\ for\ the\ Assessed\ Firm}{Maximum\ Value\ of\ Importance\ for\ the\ Assessed\ Firm}$$

4.4 Visualization of assessment results

The numeric results elaborated by means of the presented quantitative approach are characterized by a poor explanatory power. Indeed, the collection of numbers does not put forward a concrete evidence of the Industry 4.0 conformity housed in the scrutinized enterprise. As a consequence, a particular visualization form is deployed with the intention of enhancing the result comprehension. The graphical construct exceedingly qualified for the comparative representation of an elevated number of elements is denominated as radar or spider chart.

A total of five radar charts are put into operation, in order to cover the Industry 4.0 concepts in their entirety. The concepts pertaining to a specific first level dimension are packed into at least one radar chart. While the operational, organizational and socio-cultural Industry 4.0 concepts are attributable to a singular chart, the technological first level dimension units are separated into data-driven as well as process-driven technology chart that assures an enhanced representative clarity.

Table 10 presents the clear-cut allocation of technological Industry 4.0 concepts into data-driven and process-driven category as follows:

	Technological Industry 4.0 Concepts
Data-Driven	Cloud Computing
	Digital and Connected Workstations
	E-Kanban
	Internet of Things and Cyber-Physical Systems
	Cyber Security
	Artificial Intelligence
	Object Self Service
	Identification and Tracking Technology
Process-Driven	Additive Manufacturing (3D-Printing)
	Predictive Maintenance
	Tele-Maintenance
	Automated Storage Systems
	Automated Transport Systems
	Automated Manufacturing & Assembly
	Collaborative Robotics
	Smart Assistance Systems
	PDM and PLM
	CPS Standards
	VR and AR
	Simulation

Table 10: Division of technological Industry 4.0 concepts into a) data- and b) process driven concepts.

In order to finalize the description of the visualization instrument, the substance of the radar chart has to be detailed. Collectively, three different elements, which are respectively represented by the Firm Industry 4.0 Score, the Firm Industry 4.0 Target Score, and Theoretical Maximal Level. Each of them is visualized through a colored line, which is blue for the Firm Industry 4.0 Score, gray for the Firm Industry 4.0 Target Score and red for the Theoretical Maximal Level.

In conclusion, Figure 20, which serves as illustrative sample for the radar chart representation centered on the operative Industry 4.0 concepts, is presented with the aim of concretizing the avowed visualization tool.

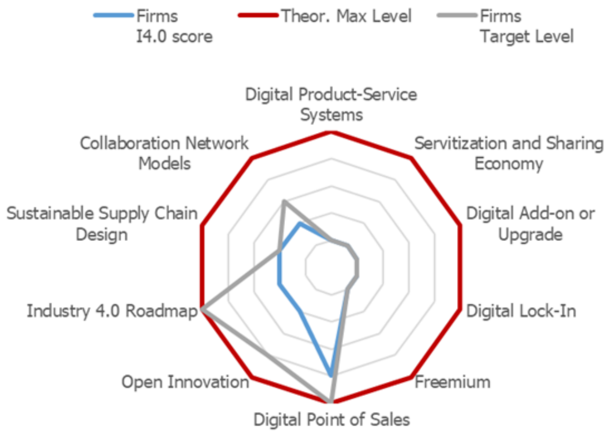

Figure 20: Radar chart sample focused on operational Industry 4.0 concepts.

4.5 Company-individual prioritization of Industry 4.0 concepts

The results obtained by means of the quantitative approach and the visualization of the analytical outcome allow to initiate the final procedural passage consisting of the specific prioritization of Industry 4.0 concepts. The objective consists in the delineation of a transparent ranking that intuitively demonstrates the urgency relating to the practical realization of Industry 4.0 concepts. The crucial quantitative parameter, which enables an objective prioritization, is represented by the Weighted Gap, which epitomizes the gravity of the Industry 4.0 immaturity. An elevated value associated to the Weighted Gap implies a high degree of urgency to put into practice specific Industry 4.0 centered measures.

The bar chart is exploited for the graphical presentation of the position table. Figure 21, which serves as illustrative sample for the bar chart representation, is introduced with the aim of concretizing the illustrated prioritization approach.

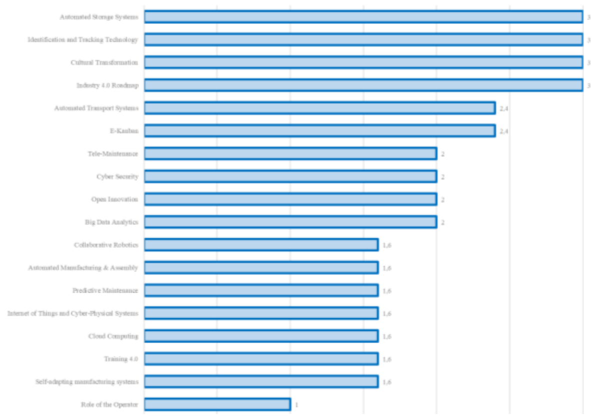

Figure 21: Bar chart sample as visualization form for the ranking of Industry 4.0 concepts.

4.6 Realization of an Excel-based assessment tool for industrial companies

The conclusive section of the fourth chapter aims at presenting the result associated to the realization of the previously conceptualized Industry 4.0 assessment tool. The mean utilized to transform the conception into an in practice implementable instrument is represented by Microsoft Excel. The mentioned software application is perfectly adapted for the descriptive representation of Industry 4.0 concepts and related maturity levels, the quantitative determination of the Firm Gap to Target and the Weighted Gap as well as for the visualization of the calculated results through the radar chart and of the prioritization by courtesy of the bar chart. Figure 22, which serves as illustrative sample for the Industry 4.0 assessment tool representation, is introduced with the aim of concretizing the illustrated concept.

										28	50		22	18
Nr.	I. Level Dimension	II. Level Dimension	Industry 4.0 concept	Maturity Level 1	Maturity Level 2	Maturity Level 3	Maturity Level 4	Maturity Level 5	Firms I4.0 score	Firms Target Level	Importance for your firm [1-5]	Firms Gap to target	Weighted Gap
1	Operation	Agile Manufacturing Systems	Agile Manufacturing system	No flexibility of manufacturing system /system produces only one kind of product with a certain capacity	Scalable manufacturing system /system is able to de/increase the volume capacity	Modular and reconfigurable manufacturing system /system is able to be adapted for other products	Flexible manufacturing system /system is able to produce different variants of a product family	Agile/changeable manufacturing system /system is designed to be utilized also for new products	4	5	5	1	1
2	Operation	Agile Manufacturing Systems	Self-adapting manufacturing systems	No adaptability of the manufacturing system /system can not be reconfigured for other products	Manual reconfiguration of manufacturing system /worker reconfigures the line manually	Semi-automted recofiguration of manufacturing system /combination of manual and auomtated reconfiguration	Automated reconfiguration of manufacturing system /worker decides the need of automated reconfiguration	Self-adapting and intelligent manufacturing system /no need for the worker to reconfigure the system	2	3	5	1	1
3	Operation	Agile Manufacturing Systems	Continuos and uninterrupted material flow models	Job Shop production /lot size production in job shop structure with semi-finished goods inventory	Cellular manufacturing /nearly continuos flow concentrated in a specific production cell	Production line /continuos flow without interruption (one-piece-flow)	Continuos flow flexible production cell/line /product knows the production sequence and goes to the next process step within the cell/line	Continuos flow flexible job shop /product knows the production sequence and goes to the next process step in the job shop	1	2	5	1	1
4	Operation	Agile Manufacturing Systems	Plug an Produce	No plug-and-produce /worker have to disassemble parts manually	Use of internally made customized connectors /connectors are not standardized and normalized	Use of existing standard connectors /connectors are standardized and normalized	Plug and produce of power supply and data /communication with need of configuration	Plug and produce of power supply and data /communication without any need of configuration	3	4	3	1	0,6
5	Operation	Monitoring & Decision Systems	Decision Support Systems	No decision making support /decisions are taken by a central decision authority	System-based information about decision making /decisions are visualized on communicated through an IT system	Data driven triggering of decision making /data analytics inform about the need for decision making	Data driven support for centralized decision making /data analytics supports central decision authorities to take a decision	Data driven support for decentralized decision making /data analytics supports operators to take a decision	1	5	5	4	4
6	Operation	Monitoring & Decision Systems	Integrated and Digital Real-Time Monitoring Systems	only paper based monitoring system /monitoring of processes is only databased and not yet digitalized	Partial Monitoring Systems /monitoring of single production processes	Partial Real-Time Monitoring Systems /real-time monitoring of single production processes	Integrated Monitoring System /monitoring is integrated in the ERP system	Integrated Real-Time Monitoring System /monitoring is real-time and integrated in the ERP system	1	5	4	4	3,2
7	Operation	Monitoring & Decision Systems	Remote Monitoring of Products	Products are not monitored /Products are not monitored after delivery	Spotwise Product Checks /Products are monitored spotwise by the customer or a sales agent or a technician	Periodic Product Checks /Products are monitored by the manufacturer through periodic condition checks	Remote Product Monitoring /Products are digitally monitored by the manufacturer through remote access	Remote Product Control /Products are monitored and controlled through remote access	1	1	1	0	0
8	Operation	Big Data	Big Data Analytics	No data analytics /no use of existing data	Manual Data Analytics of existing data /minimal use of existing data based on Excel or similar	Big Data Projects /collect data in a structured way and perform big data analytics projects through external experts	Big Data Analytics Tools /collect and analyze production and logistics data for process optimization with big data analytics tools	Internal Big Data Analytics Experts /professional application of big data analytics through skilled internal experts (production data analysts)	2	4	3	2	1,2
9	Operation	Production Planning and Control	ERP / MES Integration	no ERP system	ERP system /ERP system implemented	ERP and PPC system /Production Planning and Control system used for material requirement planning	MES implementation /MES system or similar implemented but not integrated with ERP	ERP / MES Integration /ERP and MES are integrated and communicate with each other	2	3	3	1	0,6
10	Organization	Business Models 4.0	Digital Product-Service Systems	only physical product	Maintenance business models /maintenance services sold together with product	Product Service System /extended services sold together with product	Digital Product-Service Systems /digital services sold together with the product	Web/Cloud-based Product-Service Architectures /digital services available on via web, app or cloud	1	3	4	2	1,6
11	Organization	Business Models 4.0	Servitization and Sharing Economy	Ownership based business model /Customer buys physical product (Ownership)	Leasing based business model /Customer pays the leasing rate to get ownership	Rental based business model /Customer pays a rental rate (no ownership intended)	Servitization model /customer pays for the service	Sharing Economy platform model /customers share access to products or services with other customers	1	1	1	0	0
12	Organization	Business Models 4.0	Digital Add-on or Upgrade	no Add-ons or Upgrades of products	Physical Add-on or Upgrade of the product	Digital Add-on to the product /add digital optionals in the after sales phase	Digital Upgrade of the product performance /e.g. upgrade of Tesla horsepower level	Temporary Digital Upgrade of the product performance /e.g. upgrade of Tesla horsepower over the weekend	1	2	5	1	1
13	Organization	Business Models 4.0	Digital Lock-In	no Lock-in model applicable	Physical Lock-in model /e.g. Gilette with razors and related blades	Guarantee-based Lock-in model /product guarantee ends with the use of not original parts	Light Digital Lock-in model /suggest customer to use the original OEM digital services	Digital Lock-in model /assure that no other than OEM can offer digital service	1	1	1	0	0
14	Organization	Business Models 4.0	Freemium	no after sales service required	Physical free services /free physical services in order to increase value propostion and competitive advantage	Physical Freemium /free basic services (e.g. physical maintenance check) and charged premium services (e.g. change of spare parts)	Digital free services /free digital services in order to increase value propostion and competitive advantage	Digital Freemium /free basic services (e.g. maintenance check) and charged premium services (e.g. product monitoring app)	1	1	1	0	0
15	Organization	Business Models 4.0	Digital Point of Sales	Traditional point of sales	Product pricelist on website	Web based product configurator	Web based point of sales (e-business) /e.g. online-shop	Product as a point of sales /e.g. accessing internet-shop through QR code on product	1	3	2	2	0,8
16	Organization	Innovation strategy	Open Innovation	Internal product development	Supplier integration in product development /involve supplier for problem solution and idea gathering	Open Innovation competitions or projects /single Open Innovation activities	Open Innovation Platforms /participate in Open Innovation platforms to get ideas from outside	Science Fiction Protoyping /use science fiction to describe and explore implications of futuristic technologies	2	2	3	0	0
17	Organization	Strategy 4.0	Industry 4.0 Roadmap	No strategy available	Strategy exists, but is not documented (only in minds of management)	Existing strategy and masterplan for implementation	Industry 4.0 strategy and integration of Industry 4.0 in the overall company strategy	Industry 4.0 Roadmap with defined Masterplan for stepwise implementation	3	5	5	2	2

Figure 22: Excerpt sample of Microsoft Excel Industry 4.0 assessment tool.

4.6 Conclusion of the fourth chapter

The centerpiece of the academic elaboration is represented by the fourth chapter. As a matter of fact, the development of an applicable assessment tool for Industry 4.0 implementation is performed based on a stepwise procedure. Starting from the previously established Industry 4.0 elements, the specification of comprehensible concepts is executed. In light of the defined Industry 4.0 concepts, specific maturity levels, which are composed of five distinct stages, are established. While the concepts and maturity levels form the content-related structure of the assessment tool, the determination of the quantitative assessment approach epitomizes the calculation scheme. With the intent to increase the usability of the assessment tool, the potential of visualization tools including graphs and diagrams is exploited. The final conceptional section of the assessment tool entails the prioritization of the implementation need of Industry 4.0 concepts, whose accomplishment allows the enterprise to match the aspired Industry 4.0 standards. Conclusively, the excel-based assessment tool is illustrated.

Chapter 5

VALIDATION OF THE ASSESSMENT MODEL IN INDUSTRIAL COMPANIES

The fifth section of the master thesis is devoted to the validation of the assessment model in South Tyrolean industrial enterprises. In this light, the applicability is examined thoroughly performing a case study research in two distinct industrial environments, which are respectively represented by the food- and the mechanical industry. The assessed entrepreneurial realities are characterized by a singular significant commonness, which is represented by a moderate magnitude, and several disparities, such as the operating sector and the varying degree of Industry 4.0 implementation.

As an initial step the relevant general features of the companies, which form the object of the case study, are presented. The introductory phase is followed by the illustration of the approach for the guided assessment. Each phase of the application is exhaustively presented. Subsequently, the results take the center stage. Each representation form of the assessment output, in particular the numeric and graphical, are portrayed. The conclusion of the fifth section consists of the lessons learned, whose emphasis lies on implementable corrective measure that enhance the conceptual and applicable quality of the developed Industry 4.0 assessment tool.

5.1 Presentation of the case study companies

The prefatory sub-section aims at compiling a condensed overview of the considered entrepreneurial landscape, which comprises two distinct companies. Both companies, allocated in the South Tyrolean region, are classifiable as SMEs that intend to explore the thematic area around Industry 4.0 in depth. However, despite the mentioned similarities, several discrepancies have to be denoted, above all the operational, technological and organizational nature.

Company A is perceived as an established food company within the regional industrial landscape, whose core business consists in the production of traditional and qualitative speck. The company, which is located in Naturns-South Tyrol, has been founded in the year 1974. Besides the significant success that marks the company history, one major event, namely the alliance with the notable Italian food enterprise, has to be highlighted. At present, the descendants of the founders, share the responsibility of the entrepreneurial leadership.

Company B is a South Tyrolean enterprise, whose core business comprises the production of machinery. At present, the company constitutes an essential component of a holding entrepreneurial, whose activity possesses a variegated nature that touches several realms, such as the mechanical engineering, construction as well as information technology. Company B, which is located in Brixen-South Tyrol, has been founded in the year 1964. The company is rated among the most notable regional companies thanks to the achieved success and elevated degree of internationality.

The presentation of the case study companies is finalized by the representation of essential features, such as legal form, date of incorporation, turnover, profit, total asset, employees as well as the trade description. The extracted data, which are attributable to the year 2016, are derived from the database “Analisi Informatizzata delle Aziende Italiane” (AIDA), which is considered as the central information hub of the Italian industrial landscape. The listed features of the assessed companies are presented in Table 11 as follows:

Essential Features	Company A	Company B
Trading Location	South Tyrol	South Tyrol
Legal Form	Limited Liability Company- SRL	Joint Stock Company - SPA
Turnover [€]	36.744.200	37.092.757
Profit [€]	120.964	4.160.493
Total Asset [€]	24.185.456	37.622.696
Employees	92	77
Trade Description	Production of food products	Manufacture of machinery for

Table 11: Essential features of the assessed companies [282], [283].

5.2 Approach for the guided assessment

The description of the general characteristics attributable to the enterprises Company A as well as Company B, allows to achieve a preliminary overview of the assessed industrial realities. In order to comprehend entirely how the Industry 4.0 assessment tool is put into practice, the implementation approach is portrayed. First of all, the most important characteristics consisting of the guidance has to be pointed out. Indeed, an external Industry 4.0 expert is responsible for the implementation of the assessment tool, which ideally could be represented by means of a phase model. The accomplishment of the presented Industry 4.0 assessment tool requires a total of five phases, which are respectively represented by the introduction phase, the explanation phase, the evaluation phase, the summarizing phase as well as the conclusive phase. Each passage undergone during the tool application is meticulously specified. Figure 23 summarizes graphically the approach for the guided assessment in its entirety, as follows:

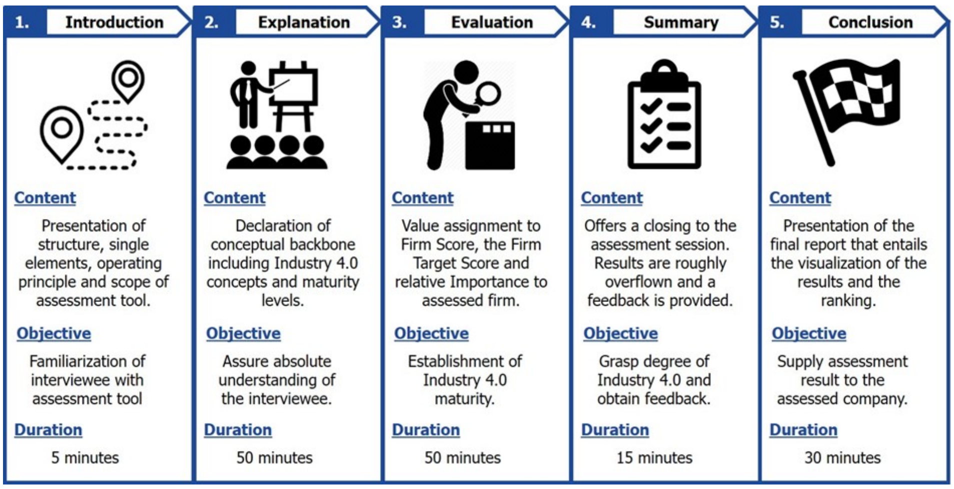

Figure 23: Phase model of the approach for the guided assessment.

The *Introduction Phase* is exploited by the Industry 4.0 interviewer to familiarize the representative of the assessed enterprise with the applied tool. In particular, the structure, the singular elements, the operating principle as well as the scope of the implementation of the Industry 4.0 tool is of interest. The prefatory remark should be concise and plain and not exceed a duration of five minutes.

The *Explanation Phase*, which assumes a crucial role within the application of the assessment tool, is dedicated to the exhaustive declaration of the conceptual backbone of the tool that consists of the Industry 4.0 concepts and the associated maturity levels. After the explication, which is characterized by brevity, accuracy as well as comprehensibility, space for questions and discussion is provided. The uppermost target pursued is to assure the absolute understanding of the conceptual section, which directly affects the quality of the assessment result. 50 minutes are dedicated for the accomplishment of the mentioned passage.

The *Evaluation Phase* is devoted to the assignment of values to three quantitative features that are epitomized by the Firm Industry 4.0 Score, the Firm Industry 4.0 Target Score as well as the Importance for the Assessed Firm. The numbers established are characterized by a firm subjective nature. While the in the previous passages the Industry 4.0 expert assumes a pivotal role, in the evaluation phase the company representative takes the center stage. The highest priority consists in the safeguarding of the judgement freedom belonging to the involved subject. The neutrality of the Industry 4.0 interviewer influences substantially the outcome of the tool application, which should reflect truthfully the Industry 4.0 reality of the enterprise. Also in this phase, a time frame of 50 minutes is planned.

The *Summarizing Phase* follows the pursue to bring to close the Industry 4.0 assessment session. The essentialities of the final results are concisely considered in order to provide a general comprehension of the overall Industry 4.0 qualities of the enterprise. Once more the interviewee moves into the spotlight by providing a feedback to the Industry 4.0 interviewer. Conclusively an outlook of the subsequent steps is supplied. A total of 15 minutes is dedicated to the completion of the last passage.

The *Conclusive Phase* is devoted to the presentation of the final report, in which all the details of the outcome associated to the Industry 4.0 assessment are entailed. Besides the numerical values, which has been discussed in the previous passage, the visual results, which are depicted by means of the radar chart as well as the prioritization ranking of the implementable Industry 4.0 concepts are illustrated. Especially the concepts, which possess a weighted gap that exceeds the value of one, are of interest and require particular attention with regard to the implementation of Industry 4.0 measures.

5.3 Assessment results

The subsection is devoted to the presentation of the results assessment sessions hold at the Company A and Company B, which are illustrated separately. In both cases, the visualization of the numeric assessment results, depicted by virtue of the radar chart, as well as the ranking of the Industry 4.0 concepts, portrayed by means of the bar chart, are presented.

5.3.1 Assessment results of Company A

As stated, the outcome of the application of the Industry 4.0 at Company A are portrayed, commencing with the visualization of the numeric results that are followed by the prioritization of the Industry 4.0 concepts.

The visualization of the assessment results entails five radar charts that are briefly interpreted.

Commencing with Figure 24 the assessment result of operation is presented.

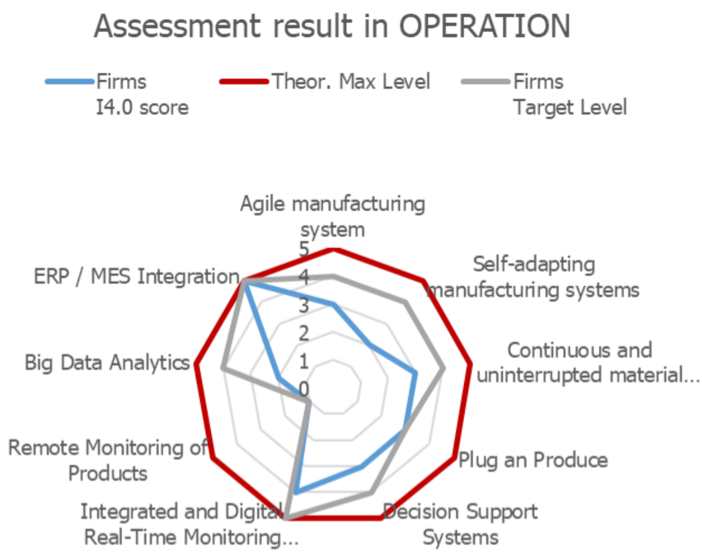

Figure 24: Assessment result in Operation of Company A.

Company A clearly focuses on specific operational Industry 4.0 concepts, such as the self-adapting manufacturing system, continuous and uninterrupted material flow mode and big data analytics, whereas the concept of remote monitoring of products is not of interest.

Figure 25 entails the assessment outcome centered on the organizational Industry 4.0 concepts.

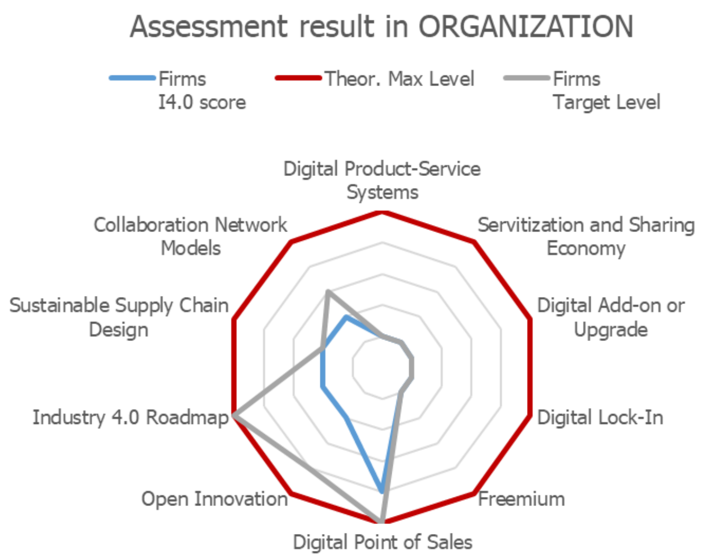

Figure 25: Assessment result in Organization of Company A.

The assessed enterprise demonstrates considerable interest in three Industry 4.0 concepts that are represented by the digital point of sale, the Industry 4.0 roadmap and the open innovation. On the other hand, several concepts are perceived as not relevant for the organization, such as the freemium, digital lock-in, digital add-on or upgrade, servitization and sharing economy and the digital product service system.

Figure 26 illustrates the assessment result related to the socio-cultural concepts.

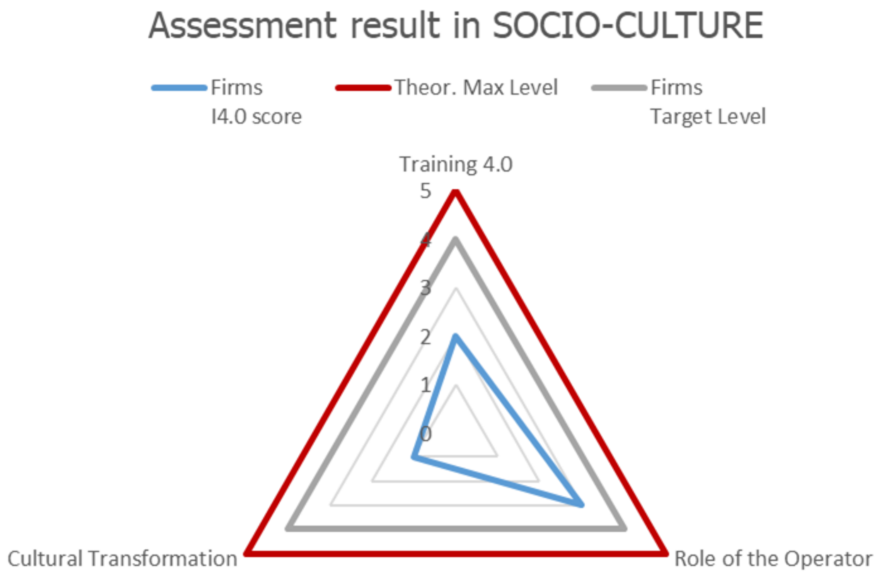

Figure 26: Assessment result in Socio-Culture of Company A.

With regard to the socio-cultural Industry 4.0 concepts, Moser Speck recognized a great need for implementation of concrete measures. Figure 27 focuses on the data-driven technological Industry 4.0 concepts.

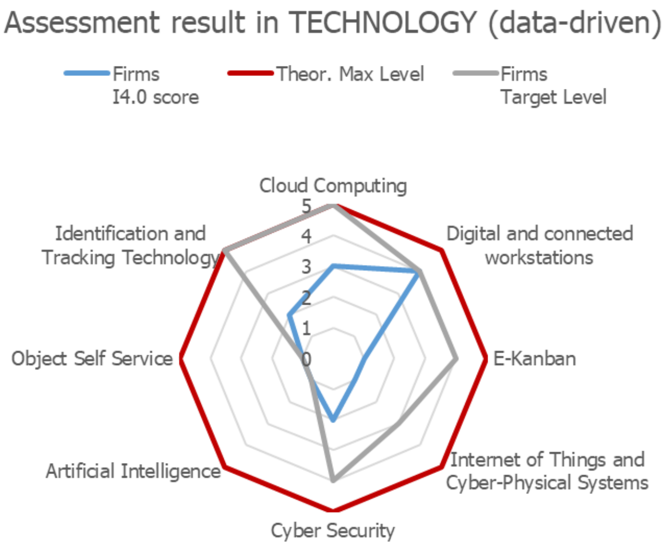

Figure 27: Assessment result in Technology (data-driven) of Company A.

Company A perceives several technological and data-driven Industry 4.0 concepts, such as identification and tracking technology, cloud computing, E-Kanban, digital and connected workstations as well as internet of things or cyber-physical systems as vitally relevant. Artificial intelligence and object self-service play a marginal role.

Conclusively, Figure 28, which put emphasis on the assessment results of the process-driven technological Industry 4.0 concepts, is invoked.

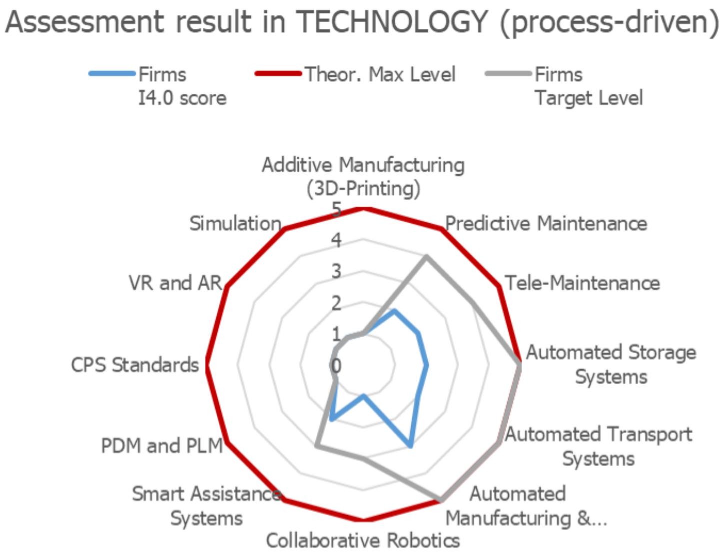

Figure 28: Assessment result in Technology (process-driven) of Company A.

Observing the radar chart, the right-shifted interest epicenter catches the eye. Indeed, automated manufacturing and assembly systems, automated storage system as well as automated transport system attract particular attention, whilst simulation, VR and AR, CPS standards, PDM and PLM, smart assistance systems as well as collaborative robots, are perceived as irrelevant topics. To finalize the assessment procedure, the ranking of the most significant Industry 4.0 concepts is illustrated by means of Figure 29.

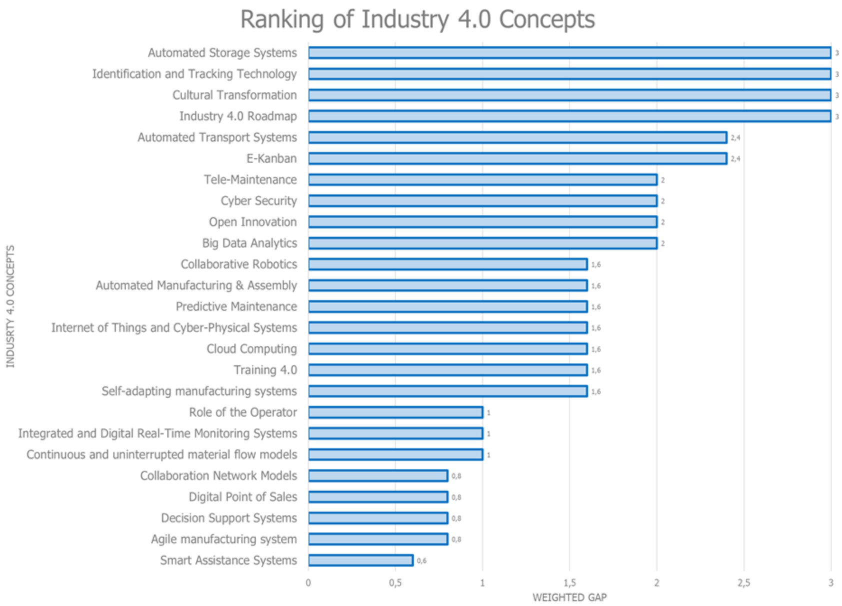

Figure 29: Ranking of Industry 4.0 concepts of Company A.

A total of 25 Industry 4.0 concepts, which exhibit a weighted gap greater than zero, are prioritized. Concepts that are perceived as irrelevant for the creation of a competitive advantage are not portrayed. The illustrated ranking serves as Industry 4.0 guideline for the Company A for the adoption of specific measures. Great relevance is devoted to automated storage system, identification and tracking technology, cultural transformation and Industry 4.0 roadmap that are equally equipped with a weighted gap of three.

5.3.2 Assessment results of Company B

The results of the implementation of the Industry 4.0 assessment tool Company B are depicted, starting with the representation of the numeric evaluation values that are followed by the prioritization of the Industry 4.0 concepts. The visualization of the assessment results entails five radar charts that are briefly interpreted. Initiating with Figure 30 the assessment result of operation is presented.

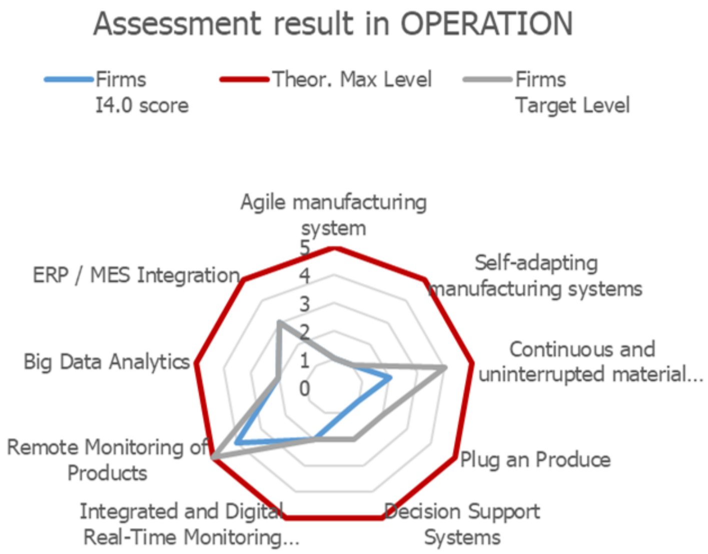

Figure 30: Assessment result in Operation of Company B.

Company B definitely emphasizes on particular operational Industry 4.0 concepts, such as the remote monitoring of products, continuous and uninterrupted material flow models as well as ERP/MES integration, whereas the concept of big data analytics, agile manufacturing system, self-adapting manufacturing system, plug and produce as well as decision support systems are not of interest. Figure 31 incorporates the assessment outcome grounded on the organizational Industry 4.0 concepts.

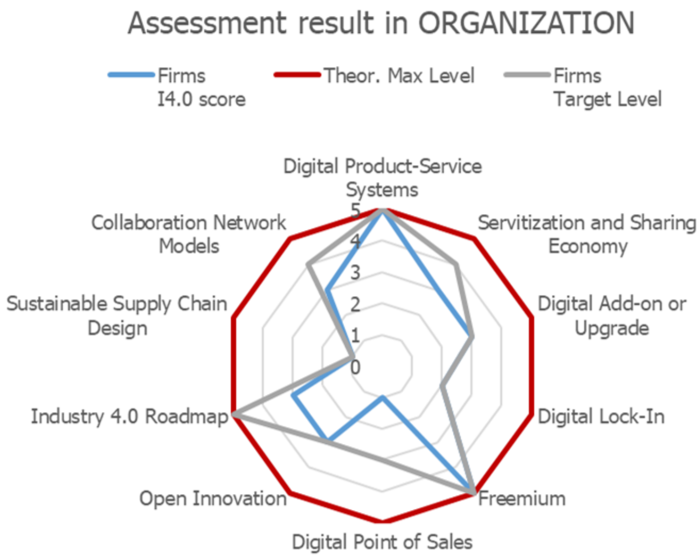

Figure 31: Assessment result in Organization of Company B.

The evaluated company concentrates on three Industry 4.0 concepts that are represented by the freemium, the Industry 4.0 roadmap and the digital product service system. On the other hand, one concept is perceived as not relevant for the organization, namely the sustainable supply chain.

Figure 32 illustrates the assessment result related to the socio-cultural concepts.

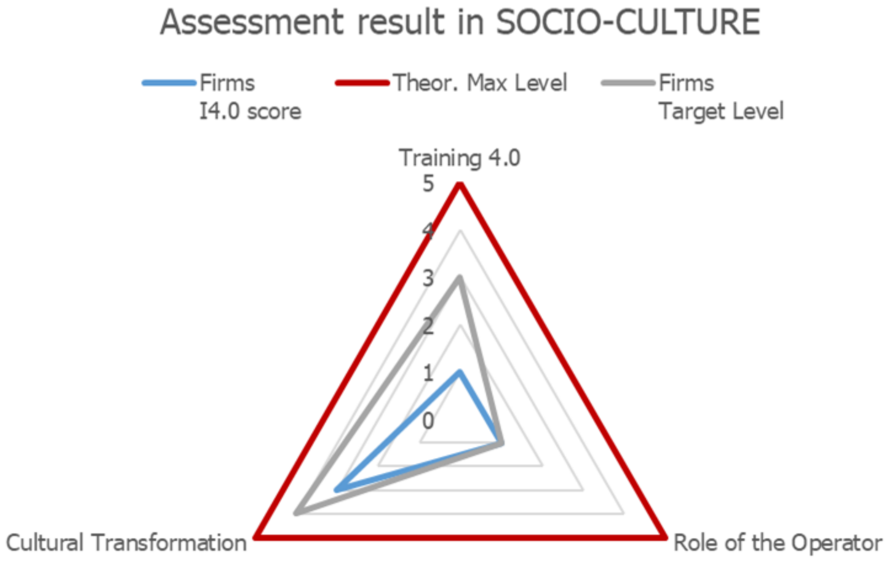

Figure 32: Assessment result in Socio-Culture of Company B.

With respect to the socio-cultural Industry 4.0 concepts, Company B recognized a great need for implementation of concrete measures. In particular for the cultural transformation and the training 4.0.

Figure 33 concentrates on the data-driven technological Industry 4.0 concepts.

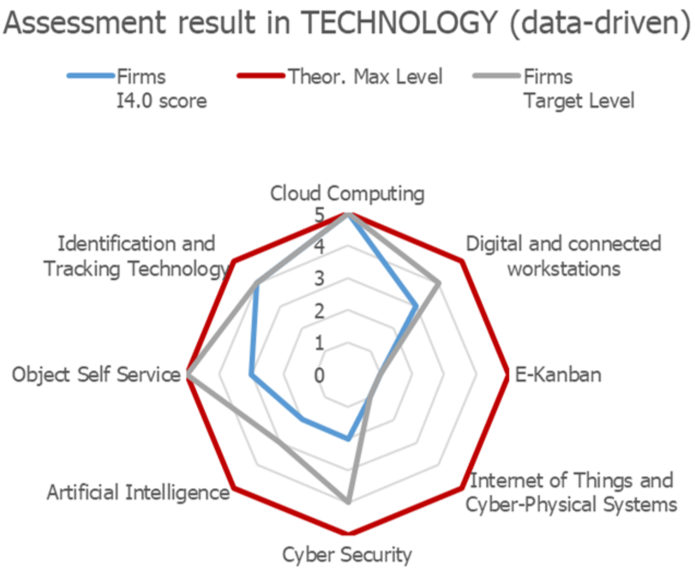

Figure 33: Assessment result in Technology (data-driven) of Company B.

Company B considers several technological and data-driven Industry 4.0 concepts, such as cyber security, object self-service, identification and tracking technology, cloud computing, digital and connected workstations as vitally relevant. E-Kanban as well as IoT and CPS play a marginal role

Conclusively, Figure 34, which puts emphasis on the assessment results of the process-driven technological Industry 4.0 concepts, is represented.

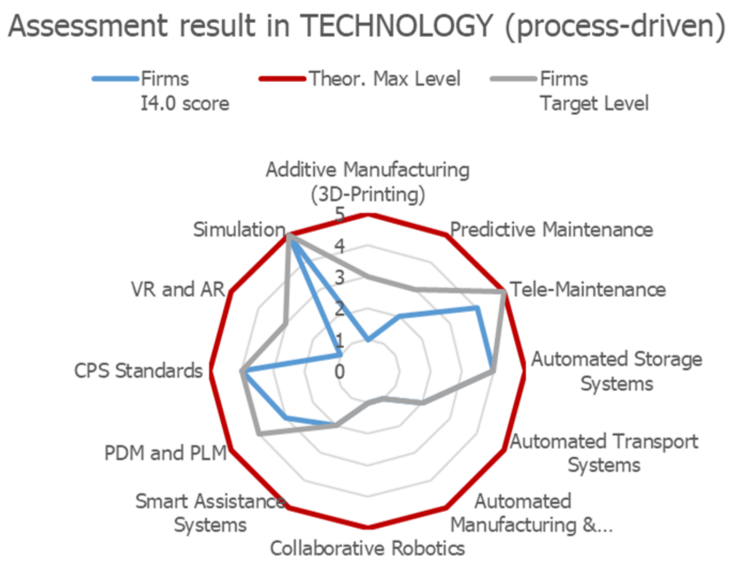

Figure 34: Assessment result in Technology (process-driven) of Company B.

The ultimate radar chart exhibits an upward-shifted interest epicenter. Indeed, simulation, tele-maintenance, automated storage system, CPS standards as well as PDM and PLM assume a central role.

To finalize the assessment procedure, the ranking of the most significant Industry 4.0 concepts is illustrated by means of Figure 35.

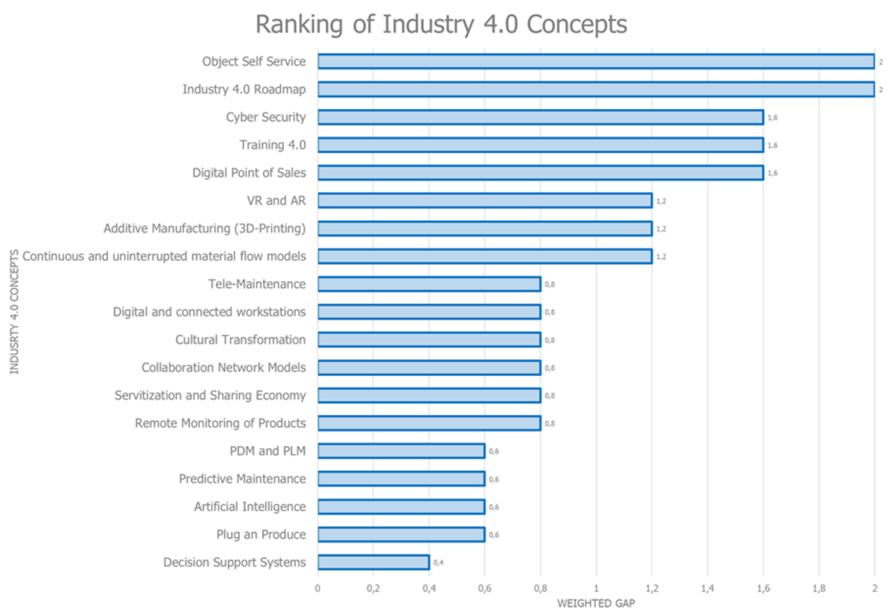

Figure 35: Ranking of Industry 4.0 concepts of Company B.

A total of 19 Industry 4.0 concepts, which possess a weighted gap greater than zero, are prioritized. Concepts that are perceived as irrelevant for the realization of a competitive advantage are not depicted. The illustrated ranking serves as Industry 4.0 guideline for the

Company B for the adoption of specific measures.

Great significance is devoted to object self-service as well as Industry 4.0 roadmap that are equally equipped with a weighted gap of two.

5.4 Lessons learned in the case studies

The deployment of the realized Industry 4.0 assessment tool in industrial realities allows to evidence the potential for improvements. In particular the feedbacks provided by the representatives of the assessed enterprises engender the necessity for slight ameliorations that affect positively the structural and implementational quality of the assessment tool.

By and large can be noted that the Industry 4.0 assessment tool convinces the interviewees, which praise the well-delineated structure, the completeness with regard to the Industry 4.0 concepts and maturity levels as well as the transparency of the quantitative approach. The Industry 4.0 concepts and the related maturity levels, which are equipped respectively with a concise description, are fully comprehendible with aid of the interviewer´s explication. The guidance provided by the interviewer is perceived by the representatives as a determinant factor for the successful completion of the Industry 4.0 assessment tool, which tackles the significant thematic realm epitomized by the latest industrial revolution.

The Industry 4.0 assessment tool offers substantial support for several decision-makers, whose ruling area is attributable to one of the uppermost level dimensions, namely operation, organization, socio-culture as well as technology. Especially for the management, the realized instrument has the potential to take root as an essential decision-making tool for Industry 4.0 matters.

Even though the tool rouses enthusiasm, a relevant negative note has been highlighted by the interviewees of both enterprises, which consists in the inappropriateness of several Industry 4.0 concepts with the nature of the entrepreneurial action. The interviewees suggest to realized sector-specific Industry 4.0 assessment tools, which are attuned to the business of a company. As a result, the instrument demonstrates an enhanced focus, which favorably affects the assessment session in terms of time and length.

5.5 Conclusion of the fifth chapter

The fifth section of the master thesis is dedicated to the validation of the assessment model in South Tyrolean industrial enterprises. In this light, the applicability is evaluated thoroughly performing a case study research in two distinct industrial environments, which are respectively represented by Company A and Company B. The assessed entrepreneurial realities are characterized by a moderate magnitude and distinct operating sectors. While Company A is considered as a relevant industrial player in the area devoted to the production of meat and poultry meat products, Company B operates in the sector of manufacture of machinery for metallurgy.

As an initial step the relevant general features of the companies, which form the object of the case study, are presented. The introductory phase is followed by the delineation of the approach for the guided assessment consisting of five phases that are respectively represented by the introduction, the explanation, the evaluation, the summary as well as the conclusion.

Subsequently, the assessment results take the center stage. Each representation form of the assessment output is presented by means of five radar charts and one bar chart, which prioritize the distinct Industry 4.0 concepts. The conclusion of the fifth section consists of the lessons learned, whose emphasis lies on implementable corrective measure that enhance the conceptual and applicable quality of the developed Industry 4.0 assessment tool. In particular, the clear focusing on specific sector has been identified as crucial improvement measure.

Chapter 6

CONCLUSIONS

The penultimate chapter of the master thesis is devoted to the determination of progressive scientific investigations related to the Industry 4.0 assessment tool. Improvement suggestions associated with the structure and the content of the instrument are cited with the intent of ameliorating its applicability. In addition, the feasibility of fundamental mutations including the abolishment of the guidance supplied by means of the interviewer, is discussed.

While the emphasis of the academic work lies on the creation of the Industry 4.0 assessment tool, further studies take a step further targeting the realization of a database, which serves as benchmark index for SMEs operating in variegated industrial sectors.

6.1 Improvement suggestions for the Industry 4.0 assessment tool

As briefly mentioned, one structural enhancement proposal is discussed. Commencing with the structure, a further categorization of the technological first level dimension is recommended. Similarly to the visual representation of the technological assessment results, a breakdown into data-driven and process-driven technological Industry 4.0 concepts is undertakable. The subtle distinction leads to an enhanced comprehensibility for the interviewee associated with the technological level dimension, which evinces the most densely conceptual population.

Passing over to the content-related amelioration, an alignment with the industrial discipline as well as with the magnitude of the assessed enterprise is pertaining to, is essential. Factually, the content of the assessment tool is tuned in terms of amount of surveyed Industry 4.0 concepts. Nevertheless, it is clear that for establishing the development of sector- as well as size-specific Industry 4.0 assessment tools, an adequate application rate is presupposed. In concrete, numerous implementations of the tool in industrial realities, which are characterized by distinct sizes and appertain to specific industrial sectors, form the fundament for the realization of sector-focused tools.

6.2 Creation of an Industry 4.0 implementation data-base

The uppermost objective followed by the Industry 4.0 assessment tool is represented by the creation of an Industry 4.0 implementation database that serves as fundament for the determination of sector- and size-specific benchmarks associated to Industry 4.0 concepts. Concretely, the target consists in the determination of a reference value for the Firms Target Level, which provides a guidance for the implementation of Industry 4.0 measures. To generate an adequate data pool, an essential feature of the assessment tool, namely the guidance, has to be revisited.

Indeed, to allow the acquisition of a considerable volume of data, the guided assessment approach, which ensures an elevated degree of comprehensibility by virtue of the explication, is replaced with an online-self-assessment approach. The first main feature of the introduced approach, namely the online nature, exponentially enhances the accessibility of the Industry 4.0 assessment tool, whilst the self-assessment facilitates the work of the interviewer, whose core competence would lie in the evaluation of the results and the establishment of a sector-specific reference value for each Industry 4.0 concept.

6.3 Conclusion of the sixth chapter

The penultimate section of the academic work concentrates on the determination of progressive scientific investigations associated to the Industry 4.0 assessment tool. Improvement suggestions associated with the structure and the content of the instrument, such as the sub-classification of the technological Industry 4.0 concepts into data- and process-driven as well as the content-adaption in terms of presented concepts volume according to industrial sector and size, are cited with the intent of ameliorating its applicability.

To enable the presence of size- and sector-specific reference values associated with each Industry 4.0 concept, a database has to be generated. The data volume, which serves as fundament for the database, derives from online-self-assessment. With respect to the implemented industry 4.0 assessment tool, some basic characteristics including the paper-basement and the guidance are drastically revisited.

Chapter 7

CONCLUSIONS

The academic work concentrates on the realization of an assessment tool associated to the implementation of Industry 4.0 for industrial realities.

The **first chapter** aims at providing a transparent overview of the master thesis' substance by exhibiting the present situation, the motivation as well as the structure of the presented work.

Based on the prefatory section, the **second chapter**, which forms the theoretical backbone of the academic work, in a first step, offers a thorough overview of the industrial revolution history as well as the definitions of Industry 4.0 and related terms. Subsequently, the fundamentals of Industry 4.0 are taken into consideration. Especially, the determination of concepts like CPS, IoT, Big Data, Smart Products, Connectivity, Additive Manufacturing, Automation, Digitalization, Work 4.0 as well as the safety and security are treated. The formation of a robust knowledge fundament permits to pass to the establishment of opportunities and threats associated to the last industrial revolution. To conclude the section dedicated to the state of the art an outline of existing assessment models and maturity stages models is realized.

The core part of the entire master thesis is represented by the **third and fourth chapter**. In fact, the realization of an applicable assessment tool for Industry 4.0 is executed. Commencing with the research methodology and approach, in which a solid methodological fundament is established, the systematic literature review is conduced. The essentiality of the literature review straightforwardly catches the eye by observing the related outcome. Concretely, the scrutinization enables the individuation of a valuable record collection from which elements epitomizing individual components of the assessment model, are filtered. The completion of the portrayed passage and the determination of dimensions and categories of Industry 4.0 concepts, allows to conceptionally realize the assessment model. The pre-requisite related to the applicability of the model within industrial environment is ensured by means of the translation of the conceptual model into an Excel-based assessment model.

The **fifth chapter** of the master thesis puts emphasis on the validation of the assessment model in South Tyrolean industrial enterprises, which are respectively represented by Company A and Company B. The assessed entrepreneurial realities categorizable as SMEs operate in distinct industrial sectors, which are epitomized by the production of meat for Company A and the manufacture of machinery for metallurgy for Company B. The assessment result of each enterprise demonstrates that either companies are in need of putting into practice concrete measures so as not to miss the Industry 4.0 train.

The gained assessment experience allows to pass over to the **sixth chapter** of the master thesis, which is devoted to the determination of progressive scientific investigations related to the Industry 4.0 assessment tool. Improvement suggestions associated with the structure and the content of the instrument, such as further categorization of the technological Industry 4.0 concepts or the creation of sector- and size specific instruments, are cited with the intent of ameliorating its applicability. In addition, the creation of a database by means of an online-self assessment tool is discussed.

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Appendix 1

SYSTEMATIC LITERATURE REVIEW

Nr	Title	Authors	Source Title	Year	Criteria
1	Strategic business transformation through technology convergence: Implications from General Electric's industrial internet initiative	Agarwal, N., Brem, A.	International Journal of Technology Management	2015	MP
2	A concept for context-aware computing in manufacturing: the white goods case	Alexopoulos, K., Makris, S., Xanthakis, V., Sipsas, K., Chryssolouris, G.	International Journal of Computer Integrated Manufacturing	2016	MP
3	Industrial operations supporting industry 4.0	Asakura, T.	NEC Technical Journal	2016	FP
4	Quality control in manufacturing plants using a factor analysis engine	Asakura, T., Ochiai, K.	NEC Technical Journal	2016	NP
5	ARTab - using Virtual and Augmented Reality Methods for an improved Situation Awareness for Telemaintenanc	Aschenbrenner, D., Maltry, N., Kimmel, J., Albert, M., Scharnagl, J., Schilling, K.	IFAC-PapersOnLine	2016	FP

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6	Tool run-out measurement in micro milling	Attanasio, A.	Micromachines	2017	NP
7	Industry 4.0: A review on industrial automation and robotic	Bahrin, M.A.K., Othman, M.F., Azli, N.H.N., Talib, M.F.	Jurnal Teknologi	2016	MP
8	Integration of Classical Components into Industrial Cyber-Physical Systems	Bangemann, T., Riedl, M., Thron, M., Diedrich, C.	Proceedings of the IEEE	2016	MP
9	Pilot Study of Readiness of Czech Companies to Implement the Principles of Industry 4.0	Basl, J.	Management and Production Engineering Review	2017	NP
10	Services enabler architecture for smart grid and smart living services providers under industry 4.0	Batista, N.C., Melício, R., Mendes, V.M.F.	Energy and Buildings	2017	NP
11	Towards decentralized production: A novel method to identify flexibility potentials in production sequences based on	Bochmann, L., Gehrke, L., Böckenkamp, A., Weichert, F., Albersmann, R., Prasse, C., Mertens, C., Motta, M., Wegener, K.	International Journal of Automation Technology	2015	FP

	flexibility graphs				
12	Quantifying the robustness of process manufacturing concept - A medical product case study	Boorla, S.M., Troldtoft, M.E., Eifler, T., Howard, T.J.	Advances in Production Engineering And Management	2017	MP
13	Big Data Solution for Quality Monitoring and Improvement on Flat Steel Production	Brandenburger, J., Colla, V., Nastasi, G., Ferro, F., Schirm, C., Melcher, J.	IFAC-PapersOnLine	2016	NP
14	Energy Optimization of Robotic Cells	Bukata, L., Sucha, P., Hanzalek, Z., Burget, P.	IEEE Transactions on Industrial Informatics	2017	NP
15	The internet information and technology research directions based on the fourth industrial revolution	Chung, M., Kim, J.	KSII Transactions on Internet and Information Systems	2016	FP
16	Using Smart Edge IoT Devices for Safer, Rapid Response with Industry IoT Control Operations	Condry, M.W., Nelson, C.B.	Proceedings of the IEEE	2016	NP
17	Smart Behavioral Filter for	Corbò, G., Foglietta, C., Palazzo, C.,	Mobile Networks and Applications	2017	MP

	Industrial Internet of Things: A Security Extension for PLC	Panzieri, S.			
18	From concept to the introduction of industry 4.0	Crnjac, M., Veža, I., Banduka, N.	International Journal of Industrial Engineering and Management	2017	FP
19	A Cloud-based Architecture for the Internet of Things targeting Industrial Devices Remote Monitoring and Control	da Silva, A.F., Ohta, R.L., dos Santos, M.N., Binotto, A.P.D.	IFAC-PapersOnLine	2016	MP
20	Product-Service Architecture (PSA): toward a Service Engineering perspective in Industry 4.0	de S. Dutra, D., Silva, J.R.	IFAC-PapersOnLine	2016	FP
21	Do Web 4.0 and Industry 4.0 Imply Education X.0?	Demartini, C., Benussi, L.	IT Professional	2017	MP
22	Atomic and close-to-atomic scale manufacturing—A trend in manufacturing development	Fang, F.	Frontiers of Mechanical Engineering	2016	NP
23	Industry 4.0: Training for automation in Europe	Fernandes, I., Assunção, E.	Welding Journal	2017	MP

24	Industry 4.0: Making the first move	Ford, M.	SMT Surface Mount Technology Magazine	2016	MP
25	Industry 4.0: Who benefits?	Ford, M.	SMT Surface Mount Technology Magazine	2015	MP
26	A knowledge-based tool for designing cyber physical production systems	Francalanza, E., Borg, J., Constantinescu, C.	Computers in Industry	2017	FP
27	Three stage maturity model in SME's towards industry 4.0	Ganzarain, J., Errasti, N.	Journal of Industrial Engineering and Management	2016	MP
28	The methodological approach to monitoring of the economic and functional state of innovation-oriented machinery engineering enterprises at the modern technological modes	Gavrysh, O., Boiarynova, K.	Economic Annals-XXI	2017	NP
29	Design for product and service innovation in industry 4.0 and emerging smart society	Gerlitz, L.	Journal of Security and Sustainability Issues	2015	MP
30	Risk based uncertainty quantification to improve	Giannetti, C., Ransing, R.S.	Computers and Industrial Engineering	2016	MP

	robustness of manufacturing operations				
31	Introduction and establishment of virtual training in the factory of the future	Gorecky, D., Khamis, M., Mura, K.	International Journal of Computer Integrated Manufacturing	2017	MP
32	Clusters and Industry 4.0–do they fit together?	Götz, M., Jankowska, B.	European Planning Studies	2017	MP
33	A new method for autonomous control of complex job shops – Integrating order release, sequencing and capacity control to meet due dates	Grundstein, S., Freitag, M., Scholz-Reiter, B.	Journal of Manufacturing Systems	2017	MP
34	Engineering the smart factory	Harrison, R., Vera, D., Ahmad, B.	Chinese Journal of Mechanical Engineering (English Edition)	2016	NP
35	Smart Industry: How ICT Will Change the Game!	Haverkort, B.R., Zimmermann, A.	IEEE Internet Computing	2017	NP
36	Digitization of industrial work: development paths and prospects	Hirsch-Kreinsen, H.	Journal for Labour Market Research	2016	NP
37	Industry 4.0 and the current status as well as future prospects	Hofmann, E., Rüsch, M.	Computers in Industry	2017	FP

	on logistics				
38	Smart factory for industry 4.0: A review	Hozdić, E.	International Journal of Modern Manufacturing Technologies	2015	MP
39	Current status, future developments and recent patents on big data technique in process control systems	Huang, Y., Xu, Y., Fang, X., Wei, B.	Recent Patents on Mechanical Engineering	2016	NP
40	Planning community energy system in the industry 4.0 era: Achievements, challenges and a potential solution	Huang, Z., Yu, H., Peng, Z., Feng, Y.	Renewable and Sustainable Energy Reviews	2017	MP
41	The fourth industrial revolution (industry 4.0): Intelligent manufacturing	Hwang, J.S.	SMT Surface Mount Technology Magazine	2016	NP
42	A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0	Ivanov, D., Dolgui, A., Sokolov, B., Werner, F., Ivanova, M.	International Journal of Production Research	2016	MP
43	Schedule coordination in cyber-physical supply networks	Ivanov, D., Sokolov, B., Ivanova, M.	IFAC-PapersOnLine	2016	MP

	Industry 4.0				
44	Quantities and sensors for machine tool spindle condition monitoring	Janak, L., Stetina, J., Fiala, Z., Hadas, Z.	MM Science Journal	2016	NP
45	Machine tool health and usage monitoring system: An initial analysis	Janak, L., Hadas, Z.	MM Science Journal	2015	NP
46	Understanding data heterogeneity in the context of cyber-physical systems integration	Jirkovsky, V., Obitko, M., Marik, V.	IEEE Transactions on Industrial Informatics	2017	NP
47	The agile approach in industrial and software engineering project management	Jovanović, M., Latić, B., Mas, A., Mesquida, A.-L.	Journal of Applied Engineering Science	2015	MP
48	Performance modeling extension of directory facilitator for enhancing communication in FIPA-compliant multiagent systems	Kadera, P., Novak, P.	IEEE Transactions on Industrial Informatics	2017	MP
49	Society. Personality. Technologies: Social	Kamensky, E.	Economic Annals-XXI	2017	NP

	Paradoxes of industry 4.0				
50	Smart manufacturing: Past research, present findings, and future directions	Kang, H.S., Lee, J.Y., Choi, S., Kim, H., Park, J.H., Son, J.Y., Kim, B.H., Noh, S.D.	International Journal of Precision Engineering and Manufacturing - Green Technology	2016	FP
51	Industry 4.0: A cost and energy efficient micro PLC for smart manufacturing	Karjagi Nigappa alias Shridhar, S., Selvakumar, J.	Indian Journal of Science and Technology	2016	NP
52	Towards a lean automation interface for workstations	Kolberg, D., Knobloch, J., Zühlke, D.	International Journal of Production Research	2017	MP
53	New logistics and production trends as the effect of global economy changes	Kovács, G., Kot, S.	Polish Journal of Management Studies	2016	MP
54	A creative prototype illustrating the ambient user experience of an intelligent future factory	Kymäläinen, T., Kaasinen, E., Hakulinen, J., Heimonen, T., Mannonen, P., Aikala, M., Paunonen, H., Ruotsalainen, J., Lehtikunnas, L.	Journal of Ambient Intelligence and Smart Environments	2017	FP
55	Autonomic Mediation Middleware for Smart Manufacturing	Lalanda, P., Morand, D., Chollet, S.	IEEE Internet Computing	2017	MP
56	PLCs as industry 4.0	Langmann, R.,	International Journal of	2016	MP

	components in laboratory applications	Rojas-Peña, L.	Online Engineering		
57	PLCs as Industry 4.0 components in laboratory applications	Langmann, R., Rojas-Peña, L.	International Journal of Interactive Mobile Technologies	2016	MP
58	Industry 4.0	Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., Hoffmann, M.	Business and Information Systems Engineering	2014	MP
59	The Requirements and solutions of 5G mobile communication for industry 4.0	Lee, H.W., Bae, K.Y.	Information (Japan)	2015	NP
60	A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems	Lee, J., Bagheri, B., Kao, H.-A.	Manufacturing Letters	2015	MP
61	A big data enabled load-balancing control for smart manufacturing of Industry 4.0	Li, D., Tang, H., Wang, S., Liu, C.	Cluster Computing	2017	MP
62	China's manufacturing locus in 2025: With a comparison of ""Made-in-China 2025"" and ""Industry	Li, L.	Technological Forecasting and Social Change	2017	NP

	4.0""				
63	A review of industrial wireless networks in the context of Industry 4.0	Li, X., Li, D., Wan, J., Vasilakos, A.V., Lai, C.-F., Wang, S.	Wireless Networks	2017	NP
64	Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal	Liao, Y., Deschamps, F., Loures, E.F.R., Ramos, L.F.P.	International Journal of Production Research	2017	FP
65	Key design of driving industry 4.0: Joint energy-efficient deployment and scheduling in group-based industrial wireless sensor networks	Lin, C.-C., Deng, D.-J., Chen, Z.-Y., Chen, K.-C.	IEEE Communications Magazine	2016	MP
66	A cross-strait comparison of innovation policy under industry 4.0 and sustainability development transition	Lin, K.C., Shyu, J.Z., Ding, K.	Sustainability (Switzerland)	2017	MP
67	Industry 4.0 and cloud manufacturing: A comparative analysis	Liu, Y., Xu, X.	Journal of Manufacturing Science and Engineering, Transactions of the ASME	2017	MP

68	Modelling the production systems in industry 4.0 and their availability with high-level Petri nets	Long, F., Zeiler, P., Bertsche, B.	IFAC-PapersOnLine	2016	NP
69	Industry 4.0: A survey on technologies, applications and open research issues	Lu, Y.	Journal of Industrial Information Integration	2017	FP
70	Internet of things (IoT) embedded future supply chains for industry 4.0: An assessment from an ERP-based fashion apparel and footwear industry	Majeed, M.A.A., Rupasinghe, T.D.	International Journal of Supply Chain Management	2017	MP
71	Problems of the time deterministic in applications for process control from the cloud	Makarov, O., Langmann, R., Nesterenko, S., Frank, B.	International Journal of Online Engineering	2014	NP
72	Decentralized decision support for intelligent manufacturing in Industry 4.0	Marques, M., Agostinho, C., Zacharewicz, G., Jardim-Gonçalves, R.	Journal of Ambient Intelligence and Smart Environments	2017	MP
73	Logistics Response to the Industry 4.0: The Physical Internet	Maslarić, M., Nikoličić, S., Mirčetić, D.	Open Engineering	2016	MP

74	Financial and economic mechanism of national forest policy implementation	Mikhailovna, C.L., Semyonovich, A.Y.	Journal of Applied Engineering Science	2016	NP
75	Link Scheduling Scheme with Shared Links and Virtual Tokens for Industrial Wireless Sensor Networks	Montero, S., Gozalvez, J., Sepulcre, M.	Mobile Networks and Applications	2016	MP
76	Sound conflict management and resolution for virtual-enterprise collaborations	Narendra, N.C., Norta, A., Mahunnah, M., Ma, L., Maggi, F.M.	Service Oriented Computing and Applications	2016	MP
77	Big data in manufacturing: a systematic mapping study	’Donovan, P., Leahy, K., Bruton, K., O’Sullivan, D.T.J.	Journal of Big Data	2015	MP
78	Understanding the implications of digitization and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry	Oesterreich, T.D., Teuteberg, F.	Computers in Industry	2016	MP
79	Designing intelligent manufacturing systems	Pacaux-Lemoine, M.-P., Trentesaux, D., Zambrano	Computers and Industrial Engineering	2017	FP

	through Human-Machine Cooperation principles: A human-centered approach	Rey, G., Millot, P.			
80	Sustainable business models and structures for industry 4.0	Prause, G.	Journal of Security and Sustainability Issues	2015	FP
81	Industry 4.0 and object-oriented development: Incremental and architectural change	Prause, M., Weigand, J.	Journal of Technology Management and Innovation	2016	MP
82	The intelligent industry of the future: A survey on emerging trends, research challenges and opportunities in Industry 4.0	Preuveneers, D., Ilie-Zudor, E.	Journal of Ambient Intelligence and Smart Environments	2017	MP
83	Proactive approach to smart maintenance and logistics as a auxiliary and service processes in a company	Rakyta, M., Fusko, M., Herčko, J., Závodská, L., Zrnić, N.	Journal of Applied Engineering Science	2016	NP
84	Industry 4.0: Implications for the Asia pacific Manufacturing Industry	Ramanathan, K.	SMT Surface Mount Technology Magazine	2015	NP

85	Enterprise systems' life cycle in pursuit of resilient smart factory for emerging aircraft industry: a synthesis of Critical Success Factors'(CSFs), theory, knowledge gaps, and implications	Rashid, A., Masood, T., Erkoyuncu, J.A., Tjahjono, B., Khan, N., Shami, M.	Enterprise Information Systems	2017	MP
86	Supply chain wide transformation of traditional industry to industry 4.0	Reddy, G.R.K., Singh, H., Hariharan, S.	ARPN Journal of Engineering and Applied Sciences	2016	MP
87	Industry 4.0 learning factory didactic design parameters for industrial engineering education in South Africa	Sackey, S.M., Bester, A., Adams, D.	South African Journal of Industrial Engineering	2017	FP
88	Industrial engineering curriculum in industry 4.0 in a South African context	Sackey, S.M., Bester, A.	South African Journal of Industrial Engineering	2016	MP
89	Enhancing process control in industry 4.0 scenarios using Cyber-Physical systems	Sánchez, B.B., Alcarria, R., Sańchez-De-Rivera, D., Sańchez-Picot, Á.	Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications	2016	MP

90	Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing	Sanders, A., Elangeswaran, C., Wulfsberg, J.	Journal of Industrial Engineering and Management	2016	FP
91	Making existing production systems Industry 4.0-ready: Holistic approach to the integration of existing production systems in Industry 4.0 environments	Schlechtendahl, J., Keinert, M., Kretschmer, F., Lechler, A., Verl, A.	Production Engineering	2014	MP
92	Requirements and concept for Plug-and-Work: Adaptivity in the context of Industry 4.0	Schleipen, M., Lüder, A., Sauer, O., Flatt, H., Jasperneite, J.	At-Automatisierungstechnik	2015	MP
93	Digital Twin Data Modeling with AutomationML and a Communication Methodology for Data Exchange	Schroeder, G.N., Steinmetz, C., Pereira, C.E., Espindola, D.B.	IFAC-PapersOnLine	2016	MP
94	Global Footprint Design based on genetic algorithms - An	Schuh, G., Potente, T., Varandani, R., Schmitz, T.	CIRP Annals - Manufacturing Technology	2014	MP

	""industry 4.0"" perspective				
95	Multipath QoS-driven routing protocol for industrial wireless networks	Sepulcre, M., Gozalvez, J., Coll-Perales, B.	Journal of Network and Computer Applications	2016	MP
96	Virtual Engineering Factory: Creating Experience Base for Industry 4.0	Shafiq, S.I., Sanin, C., Szczerbicki, E., Toro, C.	Cybernetics and Systems	2016	FP
97	Virtual engineering object (VEO): Toward experience-based design and manufacturing for industry 4.0	Shafiq, S.I., Sanin, C., Toro, C., Szczerbicki, E.	Cybernetics and Systems	2015	FP
98	Geometrical and topological approaches to Big Data	Snášel, V., Nowaková, J., Xhafa, F., Barolli, L.	Future Generation Computer Systems	2017	MP
99	Industrial revolution - Industry 4.0: Are German manufacturing SMEs the first victims of this revolution?	Sommer, L.	Journal of Industrial Engineering and Management	2015	MP
100	A computer vision assisted system for autonomous forklift vehicles in real factory	Syu, J.-L., Li, H.-T., Chiang, J.-S., Hsia, C.-H., Wu, P.-H., Hsieh, C.-F.,	Multimedia Tools and Applications	2016	FP

	environment	Li, S.-A.			
101	Process improvement trends for manufacturing systems in industry 4.0	Tamás, P., Illés, B.	Academic Journal of Manufacturing Engineering	2016	FP
102	Using autonomous intelligence to build a smart shop floor	Tang, D., Zheng, K., Zhang, H., Zhang, Z., Sang, Z., Zhang, T., Espinosa-Oviedo, J.-A., Vargas-Solar, G.	International Journal of Advanced Manufacturing Technology	2017	MP
103	Digital evaluation of sitting posture comfort in human-vehicle system under industry 4.0 framework	Tao, Q., Kang, J., Sun, W., Li, Z., Huo, X.	Chinese Journal of Mechanical Engineering (English Edition)	2016	MP
104	An event-driven manufacturing information system architecture for Industry 4.0	Theorin, A., Bengtsson, K., Provost, J., Lieder, M., Johnsson, C., Lundholm, T., Lennartson, B.	International Journal of Production Research	2017	MP
105	“Industrie 4.0” and smart manufacturing-a review of research issues and application examples	hoben, K.-D., Wiesner, S.A., Wuest, T.	International Journal of Automation Technology	2017	FP

106	UML4IoT—A UML-based approach to exploit IoT in cyber-physical manufacturing systems	Thramboulidis, K., Christoulakis, F.	Computers in Industry	2016	MP
107	External knowledge and information technology: Implications for process innovation performance	Trantopoulos, K., Von Krogh, G., Wallin, M.W., Woerter, M.	MIS Quarterly: Management Information Systems	2017	NP
108	A review of essential standards and patent landscapes for the Internet of Things: A key enabler for Industry 4.0	Trappey, A.J.C., Trappey, C.V., Hareesh Govindarajan, U., Chuang, A.C., Sun, J.J	Advanced Engineering Informatics	2016	MP
109	A Review of Technology Standards and Patent Portfolios for Enabling Cyber-Physical Systems in Advanced Manufacturing	Trappey, A.J.C., Trappey, C.V., Govindarajan, U.H., Sun, J.J., Chuang, A.C.	IEEE Access	2016	MP
110	Distributed maintenance planning in manufacturing industries	Upasani, K., Bakshi, M., Pandhare, V., Lad, B.K.	Computers and Industrial Engineering	2017	MP
111	Future maintenance: Transitioning from	Venables, M.	Plant Engineer	2017	MP

	digitalization to industry 4.0				
112	Unique Sense: Smart computing prototype for industry 4.0 revolution with IOT and bigdata implementation model	Vijaykumar, S., Saravanakumar, S.G., Balamurugan, M.	Indian Journal of Science and Technology	2015	FP
113	Guest Editorial Industry 4.0-Prerequisites and Visions	Vogel-Heuser, B., Hess, D.	IEEE Transactions on Automation Science and Engineering	2016	MP
114	Human - Robot collaboration in industry	Vysocky, A., Novak, P.	MM Science Journal	2016	FP
115	Strategic factor analysis for industry 4.0	Wahl, M.	Journal of Security and Sustainability Issues	2015	NP
116	Cloud-Assisted Cyber-Physical Systems for the Implementation of Industry 4.0	Wan, J., Xia, M.	obile Networks and Applications	2017	MP
117	Mobile services for customization manufacturing systems: An example of industry 4.0	Wan, J., Yi, M., Li, D., Zhang, C., Wang, S., Zhou, K.	IEEE Access	2016	MP
118	A hybrid-data-on-tag-enabled decentralized control system for flexible smart workpiece manufacturing	Wang, C., Jiang, P., Ding, K.	Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science	2017	MP

	shop floors				
119	Large-Scale Online Multitask Learning and Decision Making for Flexible Manufacturing	Wang, J., Sun, Y., Zhang, W., Thomas, I., Duan, S., Shi, Y.	IEEE Transactions on Industrial Informatics	2016	MP
120	Cloud-assisted interaction and negotiation of industrial robots for the smart factory	Wang, S., Zhang, C., Liu, C., Li, D., Tang, H.	Computers and Electrical Engineering	2016	MP
121	Towards smart factory for Industry 4.0: A self-organized multi-agent system with big data-based feedback and coordination	Wang, S., Wan, J., Zhang, D., Li, D., Zhang, C.	Computer Networks	2015	MP
122	Using industry 4.0 technologies to support teaching and learning	Wanyama, T.	International Journal of Engineering Education	2017	MP
123	IoT business models in an industrial context	Weinberger, M., Bilgeri, D., Fleisch, E.	At-Automatisierungstechnik	2016	FP
124	Future Modeling and Simulation of CPS-based	Weyer, S., Meyer, T., Ohmer, M., Gorecky, D.,	IFAC-PapersOnLine	2016	FP

	Factories: an Example from the Automotive Industry	Zühlke, D.			
125	Human-CPS Interaction - requirements and human-machine interaction methods for the Industry 4.0	Wittenberg, C.	IFAC-PapersOnLine	2016	MP
126	The future of industrial communication : Automation networks in the era of the internet of things and industry 4.0	Wollschlaeger, M., Sauter, T., Jasperneite, J.	IEEE Industrial Electronics Magazine	2017	NP
127	ViDX: Visual Diagnostics of Assembly Line Performance in Smart Factories	Xu, P., Mei, H., Ren, L., Chen, W.	IEEE Transactions on Visualization and Computer Graphics	2017	FP
128	Computer-Integrated Manufacturing, Cyber-Physical Systems and Cloud Manufacturing - Concepts and relationships	Yu, C., Xu, X., Lu, Y.	Manufacturing Letters	2015	MP
129	Cloud-assisted industrial cyber-physical systems: An insight	Yue, X., Cai, H., Yan, H., Zou, C., Zhou, K.	Microprocessors and Microsystems	2015	MP
130	Smart product design and production	Zawadzki, P., Zywicki, K.	Management and Production Engineering	2016	MP

	control for effective mass customization in the industry 4.0 concept		Review		
131	Industry 4.0 – An Introduction in the phenomenon	Zezulka, F., Marcon, P., Vesely, I., Sajdl, O.	IFAC-PapersOnLine	2016	FP
132	Precision glass molding: Toward an optimal fabrication of optical lenses	Zhang, L., Liu, W.	Frontiers of Mechanical Engineering	2017	NP
133	Smart spare parts management systems in semiconductor manufacturing	Zheng, M., Wu, K.	Industrial Management and Data Systems	2017	MP

Appendix 2

INDUSTRY 4.0 ASSESSMENT COMPANY A

Nr.	*I. Level Dimension*	*II. Level Dimension*	*Industry 4.0 concept*	*Maturity Level 1*	*Maturity Level 2*	*Maturity Level 3*	*Maturity Level 4*	*Maturity Level 5*	*Firm I4.0 score*	*Theor. Max Level*	*Firm Target Level*	*Importance for your firm [1-5]*	*Firm Gap to target*	*Weight Gap*
1	**Operation**	**Agile Manufacturing Systems**	**Agile manufacturing system**	No flexibility of manufacturing system */system produces only one kind of product with a certain capacity*	Scalable manufacturing system */system is able to de/increase the volume capacity*	Modular and reconfigurable manufacturing system */system is able to be adapted for other products*	Flexible manufacturing system */system is able to produce different variants of a product family*	Agile/changeable manufacturing system */system is designed to be utilized also for new products*	3	5	4	4	1	0,8
2	**Operation**	**Agile Manufacturing Systems**	**Self-adapting manufacturing systems**	No adaptability of the manufacturing system */system cannot be reconfigured for other products*	Manual reconfiguration of manufacturing system */worker reconfigures the line manually*	Semi-automated reconfiguration of manufacturing system */combination of manual and automated reconfiguration*	Automated reconfiguration of manufacturing system */worker decides the need of automated reconfiguration*	Self-adapting and intelligent manufacturing system */no need for the worker to reconfigure the system*	2	5	4	4	2	1,6
3	**Operation**	**Agile Manufacturing Systems**	**Continuous and uninterrupted material flow models**	Job Shop production */lot size production in job shop structure with semi-finished goods inventory*	Cellular manufacturing */nearly continuous flow concentrated in a specific production cell*	Production line */continuous flow without interruption (one-piece-flow)*	Continuous flow flexible production cell/line */product knows the production sequence and goes to the next process step within the cell/line*	Continuous flow flexible job shop /product knows the production sequence and goes to the next process step in the job shop	3	5	4	5	1	1
4	**Operation**	**Agile Manufacturing Systems**	**Plug an Produce**	No plug-and-produce */worker have to disassemble parts manually*	Use of internally made customized connectors */connectors are not standardized and normalized*	Use of existing standard connectors */connectors are standardized and normalized*	Plug and produce of power supply and data communication with need of configuration	Plug and produce of power supply and data communication without any need of configuration	3	5	3	3	0	0
5	**Operation**	**Monitoring & Decision Systems**	**Decision Support Systems**	No decision making support */decisions are taken by a central decision authority*	System-based information about decision making */decisions are visualized or communicated through an IT system*	Data driven triggering of decision making */data analytics inform about the need for decision making*	Data driven support for centralized decision making */data analytics supports central decision authorities to take a decision*	Data driven support for decentralized decision making */data analytics supports operators to take a decision*	3	5	4	4	1	0,8
6	**Operation**	**Monitoring & Decision Systems**	**Integrated and Digital Real-Time Monitoring Systems**	only paper based monitoring system */monitoring of processes is only databased and not yet digitalized*	Partial Monitoring Systems */monitoring of single production processes*	Partial Real-Time Monitoring Systems */real-time monitoring of single production processes*	Integrated Monitoring System */monitoring is integrated in the ERP system*	Integrated Real-Time Monitoring System */monitoring is real-time and integrated in the ERP system*	4	5	5	5	1	1
7	**Operation**	**Monitoring & Decision Systems**	**Remote Monitoring of Products**	Products are not monitored */Products are not monitored after delivery*	Spot-wise Product Checks */Products are monitored spotwise by the customer or a sales agent or a technician*	Periodic Product Checks */Products are monitored by the manufacturer through periodic condition checks*	Remote Product Monitoring */Products are digitally monitored by the manufacturer through remote access*	Remote Product Control */Products are monitored and controlled through remote access*	1	5	1	1	0	0
8	**Operation**	**Big Data**	**Big Data Analytics**	No data analytics */no use of existing data*	Manual Data Analytics of existing data */minimal use of existing data based on Excel or similar*	Big Data Projects */collect data in a structured way and perform big data analytics projects through external experts*	Big Data Analytics Tools */collect and analyze production and logistics data for process optimization with big data analytics tools*	Internal Big Data Analytics Experts */professional application of big data analytics through skilled internal experts (production data analysts)*	2	5	4	5	2	2
9	**Operation**	**Production Planning and Control**	**ERP / MES Integration**	no ERP system	ERP system */ERP system implemented*	ERP and PPC system */Production Planning and Control system used for material requirement planning*	MES implementation */MES system or similar implemented but not integrated with ERP*	ERP / MES Integration */ERP and MES are integrated and communicate with each other*	5	5	5	5	0	0
10	**Organization**	**Business Models 4.0**	**Digital Product-Service Systems**	only physical product	Maintenance business models */maintenance services sold together with product*	Product Service System */extended services sold together with product*	Digital Product-Service Systems */digital services sold together with the product*	Web/Cloud-based Product-Service Architectures */digital services available on via web, app or cloud*	1	5	1	1	0	0
11	**Organization**	**Business Models 4.0**	**Servitization and Sharing Economy**	Ownership based business model */Customer buys physical product (Ownership)*	Leasing based business model */Customer pays the leasing rate to get ownership*	Rental based business model */Customer pays a rental rate (no ownership intended)*	Servitization model */customer pays for the service*	Sharing Economy platform model */customers share access to products or services with other customers*	1	5	1	1	0	0

12	**Organization**	**Business Models 4.0**	**Digital Add-on or Upgrade**	no Add-ons or Upgrades of products	Physical Add-on or Upgrade of the product	Digital Add-on to the product *(/add digital optional in the after sales phase*	Digital Upgrade of the product performance *(/e.g. upgrade of Tesla horsepower level*	Temporary Digital Upgrade of the product performance *(/e.g. upgrade of Tesla horsepower over the weekend*	1	5	1	1	0	0
13	**Organization**	**Business Models 4.0**	**Digital Lock-In**	no Lock-in model applicable	Physical Lock-in model *(/e.g. Gilette with razors and related blades*	Guarantee-based Lock-in model *(/product guarantee ends with the use of not original parts*	Light Digital Lock-in model *(/suggest customer to use the original OEM digital services*	Digital Lock-in model *(/assure that no other than OEM can offer digital service*	1	5	1	1	0	0
14	**Organization**	**Business Models 4.0**	**Freemium**	no after sales service required	Physical free services */free physical services in order to increase value proposition and competitive advantage*	Physical Freemium */free basic services (e.g. physical maintenance check) and charged premium services (e.g. change of spare parts)*	Digital free services */free digital services in order to increase value proposition and competitive advantage*	Digital Freemium */free basic services (e.g. maintenance check) and charged premium services (e.g. product monitoring app)*	1	5	1	1	0	0
15	**Organization**	**Business Models 4.0**	**Digital Point of Sales**	Traditional point of sales	Product pricelist on website	Web based product configurator	Web based point of sales (e-business) */e.g. online-shop*	Product as a point of sales */e.g. accessing internet-shop through QR code on product*	4	5	5	4	1	0,8
16	**Organization**	**Innovation strategy**	**Open Innovation**	Internal product development	Supplier integration in product development */involve supplier for problem solution and idea gathering*	Open Innovation competitions or projects */single Open Innovation activities*	Open Innovation Platforms */participate in Open Innovation platforms to get ideas from outside*	Science Fiction Prototyping */use science fiction to describe and explore implications of futuristic technologies*	2	5	4	5	2	2
17	**Organization**	**Strategy 4.0**	**Industry 4.0 Roadmap**	No strategy available	Strategy exists, but is not documented (only in minds of management)	Existing strategy and masterplan for implementation	Industry 4.0 strategy and integration of Industry 4.0 in the overall company strategy	Industry 4.0 Roadmap with defined Masterplan for stepwise implementation	2	5	5	5	3	3
18	**Organization**	**Supply Chain Management 4.0**	**Sustainable Supply Chain Design**	No consideration of footprint or sustainability	Consideration of sustainability in Supply Chain decisions/design *e.g. local material procurement*	Consideration of sustainability in Production design */e.g. local production at customer site*	Footprint Measurement in the own value chain */measurement of footprint in production*	Global Footprint Measurement */measurement of the global footprint in the Supply Chain*	2	5	2	2	0	0
19	**Organization**	**Supply Chain Management 4.0**	**Collaboration Network Models**	No collaboration	Strategic Alliances /close collaboration with strategic partners	Collaborative Production Networks /network of manufacturer usually with a order-dispatching unit	Collaborative Cloud Manufacturing Networks /network of manufacturer that are connected and receive orders from a cloud-based system	Virtual Enterprise Network */best of everything consortium to perform a given business project to achieve maximum degree of customer satisfaction*	2	5	3	4	1	0,8
20	**Socio-Culture**	**Human Resource 4.0**	**Training 4.0**	no specific trainings	Employees are sent to specific training courses related to the job profile */train people for their job profile*	Employees have a basic knowledge about Industry 4.0 / Smart Manufacturing through training courses */creating awareness that the world is changing*	Employees have an advanced knowledge about Industry 4.0 / Smart Manufacturing through training courses */building internal know-how on Industry 4.0*	Train the Trainer - internal trainers/experts transfer their knowledge to internal employees */transfer of knowledge to all employees*	2	5	4	4	2	1,6
21	**Socio-Culture**	**Work 4.0**	**Role of the Operator**	Operator = manual work	Operator = work assisted through machines	Operator = work assisted through machines and CAx and NC tools	Operator = cooperative work through man-machine collaboration	Operator = supervisor of work aided by machines in Cyber-Physical Production Systems	3	5	4	5	1	1
22	**Socio-Culture**	**Culture 4.0**	**Cultural Transformation**	The employees have not yet been confronted with the Industry 4.0 culture	The employees were confronted with the Industry 4.0 culture, but they are skeptical about it	The employees are aware that Industry 4.0 culture is necessary for the company	The employees have partly adopted the Industry 4.0 culture	The employees largely adopted the Industry 4.0 culture	1	5	4	5	3	3
23	**Technology**	**Big Data**	**Cloud Computing**	Data is archived on single computer hard drives	Data is archived in a server structure	Data is accessible via VPN from outside the company	Software as a service models to avoid installation of applications on PC	Data is archived in a cloud system	3	5	5	4	2	1,6
24	**Technology**	**Communication & Connectivity**	**Digital and connected workstations**	Paper information on workstation	Centrally accessible Info screens in production	Mobile tablets in production	Digital workstations through screen / industrial pc on workstations	Digital and connected workstations screen / industrial pc on every workstation	4	5	4	5	0	0
25	**Technology**	**Communication & Connectivity**	**E-Kanban**	No Kanban	Bin Kanban	Card Kanban with Kanban Board	E-Kanban used for internal replenishment	E-Kanban connected with external supplier	1	5	4	4	3	2,4
26	**Technology**	**Communication & Connectivity**	**Internet of Things and Cyber-Physical Systems**	No IoT/CPS infrastructure	Sensors/actuators in production and Wi-Fi or wired LAN for data transfer	Data to information - make data available for everyone	Cognitive analysis and custom apps to optimize processes	Self-configuration, adjustment and optimization based on data	1	5	3	4	2	1,6
27	**Technology**	**Cyber Security**	**Cyber Security**	No effort for cyber security	Traditional cyber security effort (firewall, back-up,…)	Risk management matrix to analyze risk and to define the right counter-measures	Company is protected against the most risky cyber security issues	Company exceeds industry standards in cyber security	2	5	4	5	2	2
28	**Technology**	**Deep Learning, Machine Learning, Artificial Intelligence**	**Artificial Intelligence**	No application of AI	Reactive Machines */have the ability neither to form memories nor to use past experiences to inform current decisions (e.g. chess computer)*	Limited Memory */can look into the past. Self-driving cars do some of this already storing data of other cars over time*	Theory of Mind */understanding that people, creatures and objects in the world can have thoughts and emotions that affect their own behavior (not yet existing)*	Self-Awareness */conscious beings are aware of themselves, know about their internal states, and are able to predict feelings of others (not yet existing)*	1	5	1	1	0	0

29	**Technology**	**Deep Learning, Machine Learning, Artificial Intelligence**	**Object Self Service**	Customer reorders material, service or spare parts for a sold product	Seller signalizes to customer a probable need to reorder material, service or spare parts	Product signalizes need for reordering of material, services or spare parts to customer	Product signalizes need for reordering of material, services or spare parts to customer and seller	Product reorders automatically material, services or spare parts	1	5	1	1	0	0
30	**Technology**	**Identification and Tracking Technology**	**Identification and Tracking Technology**	No identification technology	Barcode label	QR-Code or similar	Passive RFID tag	Active RFID tag	2	5	5	5	3	3
31	**Technology**	**Additive Manufacturing**	**Additive Manufacturing (3D-Printing)**	No use of Additive Manufacturing	Use of Rapid Prototyping provided by specialized firms	Acquisition of basic 3D printing or rapid prototyping technology	Acquisition of advanced 3D printing, 3D scanning or rapid prototyping technology	Additive Manufacturing integrated in the production system	1	5	1	1	0	0
32	**Technology**	**Maintenance**	**Predictive Maintenance**	No maintenance strategies (reactive repair)	Preventive Maintenance */based on experience and historical data preventive*	Preventive and Automated Maintenance */system forecasts maintenance and conducts maintenance autonomously*	Predictive Maintenance */system knows that maintenance is necessary*	Predictive and Automated Maintenance */system knows that maintenance is necessary and conducts maintenance autonomously*	2	5	4	4	2	1,6
33	**Technology**	**Maintenance**	**Tele-Maintenance**	No Tele-Maintenance	Tele Maintenance via smartphone camera	Tele Maintenance via fix installed camera on machine	Remote Maintenance via remote access to the machine control	Augmented Reality to support Tele Maintenance	2	5	4	5	2	2
34	**Technology**	**Robotics & Automation**	**Automated Storage Systems**	Manual storage system	Mechanical placing and retrieving (e.g. forklift)	Mechanized storage system (e.g. with electric drives)	Automated storage system	Automated storage with optimization logic for chaotic storage	2	5	5	5	3	3
35	**Technology**	**Robotics & Automation**	**Automated Transport Systems**	Manual transport systems	Mechanical transport systems (forklift truck)	Forklift trucks with forklift control system	Track guided forklift trucks	Automated Guided Vehicles (AGV)	2	5	5	4	3	2,4
36	**Technology**	**Robotics & Automation**	**Automated Manufacturing & Assembly**	Manual manufacturing or assembly	Mechanically assisted manufacturing or assembly */e.g. with press station*	Semi-automated manufacturing or assembly */e.g. combination of manual and automated stations*	Fully automated manufacturing or assembly */dedicated automated transfer lines*	Flexible automated manufacturing or assembly */use of flexible industrial robots for various tasks*	3	5	5	4	2	1,6
37	**Technology**	**Robotics & Automation**	**Collaborative Robotics**	No use of robotic stations	Worker and robots are strictly separated	Shuttle table with a loading/unloading side (worker) and an operative side (robot)	Use of lightweight robots for collaborative robotics with force limitation	Specific security measures for collaborative robotics (e.g. virtual fence,…)	1	5	3	4	2	1,6
38	**Technology**	**Robotics & Automation**	**Smart Assistance Systems**	No worker assistance	Physical aid systems	Sensor aid systems	Cognitive Aid Systems	Self-learning assistance systems	2	5	3	3	1	0,6
39	**Technology**	**Product Design and Development**	**PDM and PLM**	No CAD software	2D CAD software	3D CAD software	PDM (Product Data Management) tools or software */manage product data*	PLM (Product Lifecycle Management) tools or software */manage product data along the product lifecycle*	1	5	1	1	0	0
40	**Technology**	**Standards 4.0**	**CPS Standards**	No standardization	Partial standardization	Physical electro-mechanical standardization	Communication standards	Standardization above industry standards	1	5	1	1	0	0
41	**Technology**	**Virtual Reality, Augmented Reality and Simulation**	**VR and AR**	No use of VR or AR	360° Videos	Virtual Reality	Augmented Reality	Mixed Reality	1	5	1	1	0	0
42	**Technology**	**Virtual Reality, Augmented Reality and Simulation**	**Simulation**	No use of simulation	Simple numerical simulations	2D simulation	3D simulation	3D discrete simulation	1	5	1	1	0	0

Appendix 3
INDUSTRY 4.0 ASSESSMENT COMPANY B

Nr.	*I. Level Dimension*	*II. Level Dimension*	*Industry 4.0 concept*	*Maturity Level 1*	*Maturity Level 2*	*Maturity Level 3*	*Maturity Level 4*	*Maturity Level 5*	*Firm I4.0 score*	*Theor. Max Level*	*Firm Target Level*	*Importance for your firm [1-5]*	*Firm Gap to target*	*Weight Gap*
1	**Operation**	**Agile Manufacturing Systems**	**Agile manufacturing system**	No flexibility of manufacturing system */system produces only one kind of product with a certain capacity*	Scalable manufacturing system */system is able to de/increase the volume capacity*	Modular and reconfigurable manufacturing system */system is able to be adapted for other products*	Flexible manufacturing system */system is able to produce different variants of a product family*	Agile/changeable manufacturing system */system is designed to be utilized also for new products*	1	5	1	1	0	0
2	**Operation**	**Agile Manufacturing Systems**	**Self-adapting manufacturing systems**	No adaptability of the manufacturing system */system cannot be reconfigured for other products*	Manual reconfiguration of manufacturing system */worker reconfigures the line manually*	Semi-automated reconfiguration of manufacturing system */combination of manual and automated reconfiguration*	Automated reconfiguration of manufacturing system */worker decides the need of automated reconfiguration*	Self-adapting and intelligent manufacturing system */no need for the worker to reconfigure the system*	1	5	1	1	0	0
3	**Operation**	**Agile Manufacturing Systems**	**Continuous and uninterrupted material flow models**	Job Shop production */lot size production in job shop structure with semi-finished goods inventory*	Cellular manufacturing */nearly continuous flow concentrated in a specific production cell*	Production line */continuous flow without interruption (one-piece-flow)*	Continuous flow flexible production cell/line */product knows the production sequence and goes to the next process step within the cell/line*	Continuous flow flexible job shop /product knows the production sequence and goes to the next process step in the job shop	2	5	4	3	2	1,2
4	**Operation**	**Agile Manufacturing Systems**	**Plug an Produce**	No plug-and-produce */worker have to disassemble parts manually*	Use of internally made customized connectors */connectors are not standardized and normalized*	Use of existing standard connectors */connectors are standardized and normalized*	Plug and produce of power supply and data communication with need of configuration	Plug and produce of power supply and data communication without any need of configuration	1	5	2	3	1	0,6
5	**Operation**	**Monitoring & Decision Systems**	**Decision Support Systems**	No decision making support */decisions are taken by a central decision authority*	System-based information about decision making */decisions are visualized or communicated through an IT system*	Data driven triggering of decision making */data analytics inform about the need for decision making*	Data driven support for centralized decision making */data analytics supports central decision authorities to take a decision*	Data driven support for decentralized decision making */data analytics supports operators to take a decision*	1	5	2	2	1	0,4
6	**Operation**	**Monitoring & Decision Systems**	**Integrated and Digital Real-Time Monitoring Systems**	only paper based monitoring system */monitoring of processes is only databased and not yet digitalized*	Partial Monitoring Systems */monitoring of single production processes*	Partial Real-Time Monitoring Systems */real-time monitoring of single production processes*	Integrated Monitoring System */monitoring is integrated in the ERP system*	Integrated Real-Time Monitoring System */monitoring is real-time and integrated in the ERP system*	2	5	2	2	0	0
7	**Operation**	**Monitoring & Decision Systems**	**Remote Monitoring of Products**	Products are not monitored */Products are not monitored after delivery*	Spotwise Product Checks */Products are monitored spotwise by the customer or a sales agent or a technician*	Periodic Product Checks */Products are monitored by the manufacturer through periodic condition checks*	Remote Product Monitoring */Products are digitally monitored by the manufacturer through remote access*	Remote Product Control */Products are monitored and controlled through remote access*	4	5	5	4	1	0,8
8	**Operation**	**Big Data**	**Big Data Analytics**	No data analytics */no use of existing data*	Manual Data Analytics of existing data */minimal use of existing data based on Excel or similar*	Big Data Projects */collect data in a structured way and perform big data analytics projects through external experts*	Big Data Analytics Tools */collect and analyze production and logistics data for process optimization with big data analytics tools*	Internal Big Data Analytics Experts */professional application of big data analytics through skilled internal experts (production data analysts)*	2	5	2	3	0	0
9	**Operation**	**Production Planning and Control**	**ERP / MES Integration**	no ERP system	ERP system */ERP system implemented*	ERP and PPC system */Production Planning and Control system used for material requirement planning*	MES implementation */MES system or similar implemented but not integrated with ERP*	ERP / MES Integration */ERP and MES are integrated and communicate with each other*	3	5	3	2	0	0
10	**Organization**	**Business Models 4.0**	**Digital Product-Service Systems**	only physical product	Maintenance business models */maintenance services sold together with product*	Product Service System */extended services sold together with product*	Digital Product-Service Systems */digital services sold together with the product*	Web/Cloud-based Product-Service Architectures */digital services available on via web, app or cloud*	5	5	5	5	0	0
11	**Organization**	**Business Models 4.0**	**Servitization and Sharing Economy**	Ownership based business model */Customer buys physical product (Ownership)*	Leasing based business model */Customer pays the leasing rate to get ownership*	Rental based business model */Customer pays a rental rate (no ownership intended)*	Servitization model */customer pays for the service*	Sharing Economy platform model */customers share access to products or services with other customers*	3	5	4	4	1	0,8
12	**Organization**	**Business Models 4.0**	**Digital Add-on or Upgrade**	no Add-ons or Upgrades of products	Physical Add-on or Upgrade of the product	Digital Add-on to the product */add digital optional in the*	Digital Upgrade of the product performance */e.g. upgrade of*	Temporary Digital Upgrade of the product performance */e.g. upgrade of*	3	5	3	3	0	0

						after sales phase	*Tesla horsepower level*	*Tesla horsepower over the weekend*						
13	**Organization**	**Business Models 4.0**	**Digital Lock-In**	no Lock-in model applicable	Physical Lock-in model */e.g. Gilette with razors and related blades*	Guarantee-based Lock-in model */product guarantee ends with the use of not original parts*	Light Digital Lock-in model */suggest customer to use the original OEM digital services*	Digital Lock-in model */assure that no other than OEM can offer digital service*	2	5	2	2	0	0
14	**Organization**	**Business Models 4.0**	**Freemium**	no after sales service required	Physical free services */free physical services in order to increase value proposition and competitive advantage*	Physical Freemium */free basic services (e.g. physical maintenance check) and charged premium services (e.g. change of spare parts)*	Digital free services */free digital services in order to increase value proposition and competitive advantage*	Digital Freemium */free basic services (e.g. maintenance check) and charged premium services (e.g. product monitoring app)*	5	5	5	5	0	0
15	**Organization**	**Business Models 4.0**	**Digital Point of Sales**	Traditional point of sales	Product pricelist on website	Web based product configurator	Web based point of sales (e-business) */e.g. online-shop*	Product as a point of sales */e.g. accessing internet-shop through QR code on product*	1	5	3	4	2	1,6
16	**Organization**	**Innovation strategy**	**Open Innovation**	Internal product development	Supplier integration in product development */involve supplier for problem solution and idea gathering*	Open Innovation competitions or projects */single Open Innovation activities*	Open Innovation Platforms */participate in Open Innovation platforms to get ideas from outside*	Science Fiction Prototyping */use science fiction to describe and explore implications of futuristic technologies*	3	5	3	4	0	0
17	**Organization**	**Strategy 4.0**	**Industry 4.0 Roadmap**	No strategy available	Strategy exists, but is not documented (only in minds of management)	Existing strategy and masterplan for implementation	Industry 4.0 strategy and integration of Industry 4.0 in the overall company strategy	Industry 4.0 Roadmap with defined Masterplan for stepwise implementation	3	5	5	5	2	2
18	**Organization**	**Supply Chain Management 4.0**	**Sustainable Supply Chain Design**	No consideration of footprint or sustainability	Consideration of sustainability in Supply Chain decisions/design *e.g. local material procurement*	Consideration of sustainability in Production design */e.g. local production at customer site*	Footprint Measurement in the own value chain */measurement of footprint in production*	Global Footprint Measurement */measurement of the global footprint in the Supply Chain*	1	5	1	1	0	0
19	**Organization**	**Supply Chain Management 4.0**	**Collaboration Network Models**	No collaboration	Strategic Alliances /close collaboration with strategic partners	Collaborative Production Networks /network of manufacturer usually with an order-dispatching unit	Collaborative Cloud Manufacturing Networks /network of manufacturer that are connected and receive orders from a cloud-based system	Virtual Enterprise Network */best of everything consortium to perform a given business project to achieve maximum degree of customer satisfaction*	3	5	4	4	1	0,8
20	**Socio-Culture**	**Human Resource 4.0**	**Training 4.0**	no specific trainings	Employees are sent to specific training courses related to the job profile */train people for their job profile*	Employees have a basic knowledge about Industry 4.0 / Smart Manufacturing through training courses */creating awareness that the world is changing*	Employees have an advanced knowledge about Industry 4.0 / Smart Manufacturing through training courses *Ibuilding internal know-how on Industry 4.0*	Train the Trainer - internal trainers/experts transfer their knowledge to internal employees */transfer of knowledge to all employees*	1	5	3	4	2	1,6
21	**Socio-Culture**	**Work 4.0**	**Role of the Operator**	Operator = manual work	Operator = work assisted through machines	Operator = work assisted through machines and CAx and NC tools	Operator = cooperative work through man-machine collaboration	Operator = supervisor of work aided by machines in Cyber-Physical Production Systems	1	5	1	1	0	0
22	**Socio-Culture**	**Culture 4.0**	**Cultural Transformation**	The employees have not yet been confronted with the Industry 4.0 culture	The employees were confronted with the Industry 4.0 culture, but they are skeptical about it	The employees are aware that Industry 4.0 culture is necessary for the company	The employees have partly adopted the Industry 4.0 culture	The employees largely adopted the Industry 4.0 culture	3	5	4	4	1	0,8
23	**Technology**	**Big Data**	**Cloud Computing**	Data is archived on single computer hard drives	Data is archived in a server structure	Data is accessible via VPN from outside the company	Software as a service models to avoid installation of applications on PC	Data is archived in a cloud system	5	5	5	5	0	0
24	**Technology**	**Communication & Connectivity**	**Digital and connected workstations**	Paper information on workstation	Centrally accessible Info screens in production	Mobile tablets in production	Digital workstations through screen / industrial pc on workstations	Digital and connected workstations screen / industrial pc on every workstation	3	5	4	4	1	0,8
25	**Technology**	**Communication & Connectivity**	**E-Kanban**	No Kanban	Bin Kanban	Card Kanban with Kanban Board	E-Kanban used for internal replenishment	E-Kanban connected with external supplier	1	5	1	1	0	0
26	**Technology**	**Communication & Connectivity**	**Internet of Things and Cyber-Physical Systems**	No IoT/CPS infrastructure	Sensors/actuators in production and Wi-Fi or wired LAN for data transfer	Data to information - make data available for everyone	Cognitive analysis and custom apps to optimize processes	Self-configuration, adjustment and optimization based on data	1	5	1	1	0	0
27	**Technology**	**Cyber Security**	**Cyber Security**	No effort for cyber security	Traditional cyber security effort (firewall, back-up,…)	Risk management matrix to analyze risk and to define the right counter-measures	Company is protected against the most risky cyber security issues	Company exceeds industry standards in cyber security	2	5	4	4	2	1,6
28	**Technology**	**Deep Learning, Machine Learning, Artificial Intelligence**	**Artificial Intelligence**	No application of AI	Reactive Machines */have the ability neither to form memories nor to use past experiences to inform current decisions (e.g. chess computer)*	Limited Memory */can look into the past. Self-driving cars do some of this already storing data of other cars over time*	Theory of Mind */understanding that people, creatures and objects in the world can have thoughts and emotions that affect their own behavior (not yet existing)*	Self-Awareness */conscious beings are aware of themselves, know about their internal states, and are able to predict feelings of others (not yet existing)*	2	5	3	3	1	0,6

29	**Technology**	**Deep Learning, Machine Learning, Artificial Intelligence**	**Object Self Service**	Customer reorders material, service or spare parts for a sold product	Seller signalizes to customer a probable need to reorder material, service or spare parts	Product signalizes need for reordering of material, services or spare parts to customer	Product signalizes need for reordering of material, services or spare parts to customer and seller	Product reorders automatically material, services or spare parts	**3**	**5**	**5**	**5**	**2**	**2**
30	**Technology**	**Identification and Tracking Technology**	**Identification and Tracking Technology**	No identification technology	Barcode label	QR-Code or similar	Passive RFID tag	Active RFID tag	**4**	**5**	**4**	**3**	**0**	**0**
31	**Technology**	**Additive Manufacturing**	**Additive Manufacturing (3D-Printing)**	No use of Additive Manufacturing	Use of Rapid Prototyping provided by specialized firms	Acquisition of basic 3D printing or rapid prototyping technology	Acquisition of advanced 3D printing, 3D scanning or rapid prototyping technology	Additive Manufacturing integrated in the production system	**1**	**5**	**3**	**3**	**2**	**1,2**
32	**Technology**	**Maintenance**	**Predictive Maintenance**	No maintenance strategies (reactive repair)	Preventive Maintenance */based on experience and historical data preventive*	Preventive and Automated Maintenance */system forecasts maintenance and conducts maintenance autonomously*	Predictive Maintenance */system knows that maintenance is necessary*	Predictive and Automated Maintenance */system knows that maintenance is necessary and conducts maintenance autonomously*	**2**	**5**	**3**	**3**	**1**	**0,6**
33	**Technology**	**Maintenance**	**Tele-Maintenance**	No Tele-Maintenance	Tele Maintenance via smartphone camera	Tele Maintenance via fix installed camera on machine	Remote Maintenance via remote access to the machine control	Augmented Reality to support Tele Maintenance	**4**	**5**	**5**	**4**	**1**	**0,8**
34	**Technology**	**Robotics & Automation**	**Automated Storage Systems**	Manual storage system	Mechanical placing and retrieving (e.g. forklift)	Mechanized storage system (e.g. with electric drives)	Automated storage system	Automated storage with optimization logic for chaotic storage	**4**	**5**	**4**	**4**	**0**	**0**
35	**Technology**	**Robotics & Automation**	**Automated Transport Systems**	Manual transport systems	Mechanical transport systems (forklift truck)	Forklift trucks with forklift control system	Track guided forklift trucks	Automated Guided Vehicles (AGV)	**2**	**5**	**2**	**3**	**0**	**0**
36	**Technology**	**Robotics & Automation**	**Automated Manufacturing & Assembly**	Manual manufacturing or assembly	Mechanically assisted manufacturing or assembly */e.g. with press station*	Semi-automated manufacturing or assembly */e.g. combination of manual and automated stations*	Fully automated manufacturing or assembly */dedicated automated transfer lines*	Flexible automated manufacturing or assembly */use of flexible industrial robots for various tasks*	**1**	**5**	**1**	**1**	**0**	**0**
37	**Technology**	**Robotics & Automation**	**Collaborative Robotics**	No use of robotic stations	Worker and robots are strictly separated	Shuttle table with a loading/unloading side (worker) and an operative side (robot)	Use of lightweight robots for collaborative robotics with force limitation	Specific security measures for collaborative robotics (e.g. virtual fence,…)	**1**	**5**	**1**	**1**	**0**	**0**
38	**Technology**	**Robotics & Automation**	**Smart Assistance Systems**	No worker assistance	Physical aid systems	Sensor aid systems	Cognitive Aid Systems	Self-learning assistance systems	**2**	**5**	**2**	**2**	**0**	**0**
39	**Technology**	**Product Design and Development**	**PDM and PLM**	No CAD software	2D CAD software	3D CAD software	PDM (Product Data Management) tools or software */manage product data*	PLM (Product Lifecycle Management) tools or software */manage product data along the product lifecycle*	**3**	**5**	**4**	**3**	**1**	**0,6**
40	**Technology**	**Standards 4.0**	**CPS Standards**	No standardization	Partial standardization	Physical electro-mechanical standardization	Communication standards	Standardization above industry standards	**4**	**5**	**4**	**4**	**0**	**0**
41	**Technology**	**Virtual Reality, Augmented Reality and Simulation**	**VR and AR**	No use of VR or AR	360° Videos	Virtual Reality	Augmented Reality	Mixed Reality	**1**	**5**	**3**	**3**	**2**	**1,2**
42	**Technology**	**Virtual Reality, Augmented Reality and Simulation**	**Simulation**	No use of simulation	Simple numerical simulations	2D simulation	3D simulation	3D discrete simulation	**5**	**5**	**5**	**4**	**0**	**0**