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The Concept Industry 4.0

An Empirical Analysis of Technologies and Applications in Production Logistics

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Preface

The present master thesis has been written in context of a double-degree program with the Technical University of Berlin (Germany) and the Tongji University in Shanghai (China). The research and writing process started in November 2014 and went until July 2015.

The vision for this thesis and the corresponding research questions have been jointly developed with my thesis supervisor, Mr. Daniel Roy, who was research associate at the logistics chair of Mr. Prof. Dr.-Ing. Frank Straube at the Technical University of Berlin at that time. The fact, that we could possibly lay at least a small part of foundation in the barely unexplored field of “Industry 4.0” has considerably driven our motivation during the whole research project. I would like to thank my supervisor for his excellent guidance and support during this process.

I also like to thank all of the respondents of my questionnaire, without whose cooperation I would not have been able to conduct the master thesis’ results.

Special thanks goes to my family and friends. I benefitted from debating issues and developing cooperatively new ideas. My wife deserves a particular note of thanks: your wise counsel and kind words have, as always, served me well and helped me to stay focused.

I hope you enjoy reading.

Christoph Jan Bartodziej

Overview

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List of Abbreviations

AI	Artificial Intelligence
Auto-ID	Automatic Identification
BCG	The Boston Consulting Group
Cf.	compare
CPS	Cyber-Physical-System
DIN	Deutsches Institut für Normung (German Institute for Standardization)
E.g.	exempli gratia
ERP	Enterprise Resource Planning
FD	Field Device
GE	General Electric
HMI	Human-Machine-Interface
ICT	Information and communication technology
IIC	Industrial Internet Consortium
IaaS	Infrastructure-as-a-Service
IoT	Internet of Things
IoS	Internet of Services
IoTS	Internet of Things and Services
M2M	Machine-to-Machine (Communication)
MAS	Multi-agent system
MES	Manufacturing Execution System
MFC	Material Flow Computer
PaaS	Platform-as-a-Service
P.	page
PLC	Programmable Logic Controller
RAM	Random Access Memory
RFID	Radio Frequency Identification
ROM	Read-Only Memory
SaaS	Software-as-a-Service
SMEs	Small and medium-sized enterprises
TCP/IP	Transmission Control Protocol/ Internet Protocol
TIM	Technology and innovation management
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
WLAN	Wireless Local Area Network

1 Introduction

The introduction into this thesis gives a brief description on the underlying research problem, the objective of the thesis, the research questions and method as well as a summary of the thesis outline.

1.1 Problem definition

The manufacturing industry is currently subject to huge change. This change is caused by various ongoing global megatrends such as globalization, urbanization, individualization, and demographic change, which will considerably challenge the entire manufacturing environment in the future.[1] On the one hand, an increase of worldwide-connected business activities will raise the complexity within manufacturing networks. On the other hand, a volatile demand and customized products of the companies will influence the production and planning processes additionally.[2] These challenging requirements will force companies to adapt their entire manufacturing approach including structure, processes, and products.[3]

Due to the fact, German manufacturing industry represents a high proportion (approx. 25.9% in 2014)[4] of the gross domestic product (GDP) and every second workplace is either directly or indirectly[5] related to manufacturing, it is vital to strengthen the competitiveness of manufacturing industry in the future.[6] The German government, therefore, launched the “strategic initiative” **Industry 4.0** in January 2011, which is coordinated by industrial and scientific organizations. Within the scope of Industry 4.0, which was adopted as part of the High-Tech Strategy 2020 Action Plan in November 2011, a general framework will be elaborated based on technical, economical, and socio-political parameters aiming to promote the industrial change and, consequently, ensure German market competitiveness in the world.[7]

Industry 4.0 means fourth industrial revolution.[8] This stage of the industrialization process is, as well as the three previous stages, dominated by technical innovations. While mechanization and electrification of manufacturing processes has led to the first two industrial revolutions, the third stage, which is characterized by an increase of

[1] Cf. Westkämper, E. (2013), p. 7
[2] Cf. Abele, E.; Reinhart, G. (2011), p.11
[3] Cf. Spath et al. (2013), p.42
[4] Cf. Federal Statistical Office (2015), p. 1, also note: Manufacturing industry does not include construction industry.
[5] Jobs from the service sector, which are indirectly connected and dependent on manufacturing.
[6] Cf. Kagermann et al. (2013), p. 17ff.
[7] Cf. BMBF (2014), p. 2
[8] Cf. Kagermann et al. (2013), p. 33

C.J. Bartodziej, *The Concept Industry 4.0*, BestMasters,
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informatization and automatization, is currently smoothly transforming into the next industrial revolution.[9] Industry 4.0 is marked by a technical integration of Cyber-Physical-Systems in manufacturing and logistics processes as well as the use of the Internet of Things and Services in industrial processes. New technologies will have miscellaneous impact on value creation, work organization, downstream services, and business models of companies.[10] At the forefront of all Industry 4.0 developments, the concept of a Smart Factory plays a significant role in shaping the vision of a new industrial age. In current literature and scientific journals, experts are mentioning a complete paradigm shift in manufacturing[11]. It is said, that a decentralized, self-organizing, and flexible production environment will replace the classical, centrally controlled production hierarchy.[12]

A dual strategy is forming the base for enhancing German market potential in this area to ideally implement the ideas of the "strategic initiative". On the one hand, an increased deployment of Cyber-Physical-Systems in German factories will strengthen German manufacturing industry by improving the efficiency of domestic production (leading market strategy). On the other hand, the development of Cyber-Physical-Systems technology offers significant opportunities for exporting technologies and products and, thus, keeping up as world leading manufacturing equipment supplier (leading supplier strategy).[13]

1.2 Objectives

According to the relevance of the topic Industry 4.0, it is essential to clarify terminology, explain relations, and identify drivers and barriers for the implementation of Industry 4.0 technologies, as Industry 4.0 is quite an unexplored field of activity in terms of academic research as well as of industrial use. On the one hand, technology suppliers are uncertain about the needs of potential Industry 4.0 customer. On the other hand, technology users are uninformed about the prejudices of new technologies and thus have difficulties to implement them. A viable approach to tackling this issue from both perspectives is to build a bridge between technologies and customer needs by description and evaluation of technology functions. Hence, the purpose of this thesis is to examine which potential Industry 4.0 technologies do have regarding end-to-end digital integration in production logistics based on their functions. The results will

[9] Cf. Bauernhansl, T. (2014), p. 5ff.
[10] Cf. Kagermann et al. (2013), p. 18
[11] The terms „manufacturing“ and „production“ are used as synonyms in this thesis.
[12] Cf. Bauernhansl, T. (2014), p. 31
[13] Cf. Kagermann et al. (2013), p. 33ff.

constitute a profound basis to formulate recommendations for action for technology suppliers and technology users.

At first, technologies in the field of Industry 4.0 will be identified and systemized according to proven technology classification models in the literature (key technologies, basic technologies and technology paradigm). Based on an extensive literature review, the functions of these technologies will be elaborated and defined within the context of this thesis. By means of an empirical study the influence of these functions, their practical relevance, and their market readiness will be explored. Based on these three elements, the technology potential of the identified technologies can be derived. To make these functions applicable to production logistics, technology paradigm, in the wider field of production logistics, will be determined through an analysis of Industry 4.0 use cases and research programs, and the applicability of the technologies and functions will be shown.

1.3 Research questions and method

The above-described objective of this thesis leads to the following primary research question:

> *„Which potential do Industry 4.0 technologies have regarding end-to-end digital integration with a focus on production logistics? “*

It is pivotal to successively work out the four following secondary research questions to answer the primary research question.[14]

1. *What is Industry 4.0? (R1 - Chapter 3)*

2. *Which technologies exist in the field of Industry 4.0? Which functions do the technologies offer? (R2 - Chapter 4)*

3. *How big is the influence of the identified technological functions on end-to-end digital integration, what is their practical relevance, and when will they reach market readiness? (R3 - Chapter 5)*

[14] The elaboration of the fourth secondary research question is in contrary to the three previous ones not a prerequisite to answer the primary research questions adequately. It has to be perceived as integral part of the primary research question.

4. *Which recommendations for action for technology suppliers, as well as for technology users, can be derived? (R4 - Chapter 6)*

In theory of science, a distinction is made between formal sciences and real sciences.[15] Business management and administration is a subfield of social science and, therefore, has to be allocated among real sciences.[16] Production logistics as part of the entire logistics process and technology studies are interdisciplinary, application-oriented sciences [17] , which have functions in business management and administration. Consequently, this research project is subject to real sciences in terms of scientific theories. The main objective of real sciences is to describe and explain real facts to derive substantial, empirical knowledge (theories), which later on can be validated (verification, falsification).[18]

Due to the relative broadly formulated research questions, an exploratory research design was selected. Furthermore, the research methods mostly have qualitative fundaments, as qualitative methods seek to gain scientific knowledge. The use of qualitative research methods is, in particular, suitable for relatively unexplored areas such as Industry 4.0, as problems might be seen and tackled from different perspectives [19] . Hennink et al. state that qualitative research is most suitable for addressing "why" questions to understand issues or "how" questions that describe processes or behavior.[20]

Within the scope of this work, an empirical study based on an online questionnaire will be the primary source of data collection to answer the research question ideally. The substantive preparatory work for the creation of the questionnaire is based on a scientific literature review. Incorporating theoretical literature to a qualitative research design is pivotal as Hennink et al. (2010) conclude. They claim that qualitative research always is embedded in an existing theory and never made "out of the blue."[21] The extensive literature review in this thesis is based on a snowball procedure. This procedure is derived from a research method, which is called snowball sampling. "Snowball," in this case, refers to the process of data accumulation, in which the researcher starts to collect data from only a few members of the target population and then continues with other individuals that have been recommended by the first members and so on.[22] As the

[15] Cf. Kornmeier, M. (2007), p. 14
[16] Cf. Burschel, C. (2004), p. 1942
[17] Cf. Delfmann et al. (2011), p. 1
[18] Cf. Kornmeier, M. (2007), p. 13ff.
[19] Cf. Bortz, J.; Döring, N. (2006), p. 54ff.
[20] Cf. Hennink et al. (2010), p. 10
[21] Ibid., p. 34
[22] Cf. Babbie, E. R. (2011), p. 208

overall topic Industry 4.0 is quite unexplored, only a few fundamental works in literature exist. The process starts with screening the basic literature and goes further with processing literature[23] with semantic relation to the topic. This process finally leads to a structured literature review, which has a valid foundation for scientific research.

Additional various experiences and observations will be consulted, which have been made within the scope of this thesis through non-standardized conversations with experts in this area and several visits to conferences and other seminars.

1.4 Thesis outline

The outline of the thesis targets to answer the objectives and research questions, which were mentioned explicitly in **chapter 1**.

In **chapter 2,** the theoretical background for this thesis will be set. Important terminology will be explained and directly linked to the context of this thesis. First, the management of new technologies will be described by introducing concepts such as technology classification models and technology, and innovation management. Followed by an explanation of the term function, which is, in particular, suitable criteria for identifying technology potential, as it serves as a fundamental connection between technologies and products and, therefore, links supply and demand.
Afterwards the production logistics process, which is seen as a vital link between procurement and distribution processes in business management, will be explained with its essential components and tasks.

Chapter 3 will present a holistic description of the concept Industry 4.0. Initially the drivers for this development will be explained. After defining all important terms in the context of Industry 4.0, a brief comparison is made between the German concept and similar, internationally related ideas/ visions. The predicted economic potential of this vision will be presented. Furthermore, the key feature of Industry 4.0, namely the Smart Factory, will be explained, and a special focus will be placed on the meaning and requirements for end-to-end digital integration in production logistics.

Chapter 4 investigates technologies under the umbrella of Industry 4.0 and their functions. This chapter has a crucial meaning for the thesis, as the findings will be the starting point for the empirical study. Technologies will be identified, systemized, and analyzed according to their functions. The initial point for the analysis will be the key

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[23] The process is based on footnotes, authors and register of persons.

technologies of Industry 4.0, namely Cyber-Physical-Systems and the Internet of Things and Services.

In **chapter 5,** the procedure of the online questionnaire will be described, statistical methods for the analysis of data presented and the analysis of the results executed. The findings will be the foundation for the identification of technology potential in a Smart Factory environment concerning end-to-end digital integration and, thus, be pivotal to answer the primary research question.

In **chapter 6,** the technology potential of the key technology, the basic technologies and technology paradigms of Industry 4.0 will be derived based on the results of the empirical study. The examination of technology potential allows deriving special recommendations for action. The recommendations might provide meaningful aspects for further research and development areas as well as for new technology applications in the manufacturing industry.

Chapter 7 will provide a conclusion on the research initiative and give an outlook on further research needs in the examined field.

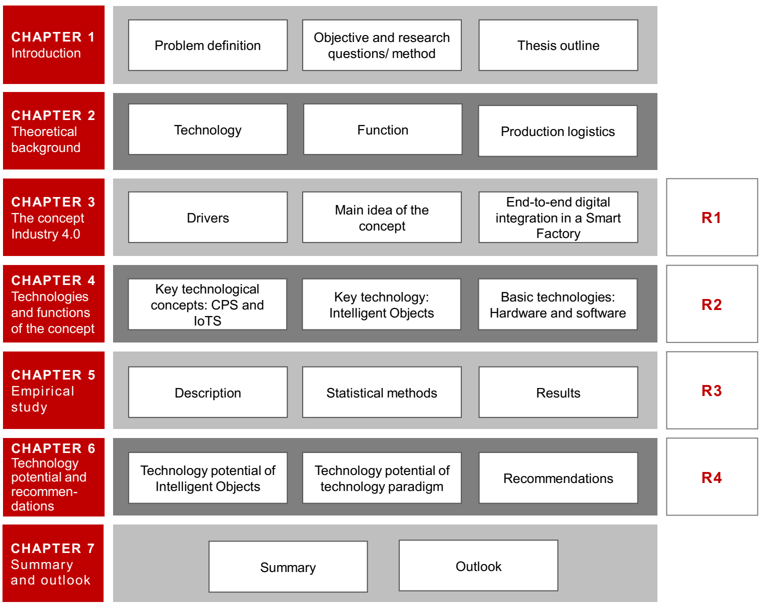

Figure 1: Thesis outline

(Source: Own representation)

2 Theoretical background

In the following section, the theoretical basis for a comprehensible understanding of this thesis will be described. The focus will be set on the management of new technologies, the theoretical concept of functions, and the production logistics process.

2.1 Management of new technologies

Initially, the terms "technology" and "technology paradigm" will be defined and distinguished from similar notions in context of this thesis. The importance of managing new technologies in companies will be highlighted using theoretical concepts to classify technologies based on time and stages of their development.

2.1.1 Technology definition

The definition and distinction of the term "technology" in literature is and always was very controversially discussed. In German language, there is a distinction in content between the terms "Technologie" and "Technik"[24], whereas in English literature both terms are subsumed under the term "technology".[25] The German terms are often mixed up, as there is missing a uniform definition of both terms.[26] As "technologies" are in focus of this thesis, it is vital to have a closer look at the origin of the term and its understanding.
The term "technology" is based on the Greek term "technikos," which means craftsmanship and skillful procedures.[27] The original meaning of the word did change over the centuries, so that one of the latest definitions of "technology", namely "science of art" is still insufficient as it leaves a lot of room for interpretation.[28] Perl defines the term "Technologie" as application-oriented, universally valid relations between ends and means. "Technologie" is a scientific-technical response relationship, which provides adequate possibilities for action in certain application areas.[29] Kroell defines three important statements on the term "Technologie":[30]

- Knowledge of scientific-technical relations, as long as its applied to solutions of technical problems, which are connected to economic, organizational, social, and political elements
- Proficiency and skills to solve technical problems
- Resources that are intended to implement scientific knowledge into practice

[24] Cf. Zahn, E. (1995), p. 4
[25] Cf. Schuh et al. (2011), p. 33 and cf. Gerpott, T. J. (2005), p. 18
[26] Cf. Kröll, M. (2007), p. 25
[27] Cf. Schuh et al. (2011), p. 33
[28] Cf. Spur, G. (1998), p. 77
[29] Cf. Perl, E. (2007), p. 18
[30] Cf. Kröll, M. (2007), p. 24

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In summary, the term “Technologie” describes technical knowledge, namely proficiency, skills, and possibilities for the development and application of “Technik” in specific areas.[31]

Having discussed that, a definition of the term “Technik” has to be formulated. Brockhoff constitutes that “Technik” is a realized, applied element of a “Technologie”. It is the materialization of “Technologie” in products (objects)[32] or procedures, which have the intention to solve technical problems.[33] A “Technologie” can be implemented in one or more “Technik”.[34] Kroell concludes two main descriptions for the term “Technik”:[35]

- Material result of a problem-solving process as well as the related production and use of the same
- Realized products, equipment, materials, transformation processes, and transformation procedures

Consequently, “Technik” is the concrete existence and instrumentalization of technical objects.[36] Even though there is some conformity on the definition of the terms “Technologie” and “Technik” in literature, a distinction of both terms in this thesis is not necessary as (a) it is insufficient to proceed based on uncertainties, and (b) it is not expedient according to the topic and the research questions of this thesis. With the use of the term “technology paradigm” in the next section a precise distinction of the term “technology” is made. Moreover, the use of the terms “Technik” and “Technologie” in common parlance is subject to change due to its influence based on the English-American understanding of the term “technology”.[37] Therefore, it is smart to choose a more straightforward, though very appropriate definition of the term “technology” in this thesis, which is based on literature of the American National Academy of Engineering:[38]

"Technology is the means by which human life is improved."

2.1.2 Theory of technology paradigm

Having defined and distinguished the term “technology,” based on literature, it is vital to have a closer look at another term in conjunction with the management of new technologies – the technology paradigm. Within the scope of technology management, it seems that companies, in particular, have problems with managing technological

[31] Cf. Spur, G. (1998), p. 77
[32] Cf. Zahn, E. (1995), p. 4
[33] Cf. Gerpott, T. J. (2005), p. 18
[34] Cf. Peine, A. (2006), p. 18
[35] Cf. Kröll, M. (2007), p. 24
[36] Ibid.
[37] Cf. Spur, G. (1998), p. 77
[38] Ibid., p. 83f.

innovations if new products and procedures are connected to a different technological paradigm[39]. An example of a technological paradigm shift is the transformation from centralized, isolated to decentralize, networked computer architecture.[40] As new technologies are characterized by new paradigm and new functionalities, which are developed based on scientific knowledge and have an enormous impact on existing structures in industry, an understanding of the term "technology paradigm" is essential.[41]

Thomas Kuhn, seen as the founder of the theory of paradigm, defines the term "scientific paradigm" in the late 1970's by using two key features of this idea:[42]

- On one hand, the term "paradigm" stands for the whole constellation of opinions, values, methods, and so forth, which are shared among members of a certain community.
- On the other hand, the term "paradigm" stands for elements of the given constellation, **which are concrete problem-solving components and are used as idols or examples to replace existing scientific solutions. Kuhn describes them as model solutions**[43].

In broad analogy with the Kuhnian definition of a "scientific paradigm", Dosi defines, in his classic article in 1982, a "technological paradigm" as
"[…] 'model' and a 'pattern' of solution of selected technological problems based on selected principles derived from natural sciences and on selected material technologies."[44]

Tunzelmann et al. worked out the importance of Dosi's paper for the theory of paradigm. They claim that the academic impact of the original paper is considerable and makes it one of the most highly cited papers in economics and technical change as it has received more than 670 ISI citations until 2008.[45] Based on the relevance of Dosi's paper, his definition of "technological paradigm" will be used in this thesis.

2.1.3 Technology classification based on technology types

In literature, there are many alternatives to classify technologies. An appropriate classification method is to systemize technologies based on their current stage of development (maturity) and their importance for industry, customer, and business

[39] The terms "technological paradigm" and "technology paradigm" are used as synonyms in this thesis.
[40] Cf. Gerpott, T. J. (2005), p. 2f.
[41] Cf. Heubach, D. (2008), p. 30
[42] Cf. Kuhn, T. S. (1976), p. 186
[43] Cf. Peine, A. (2006), p. 48
[44] Dosi, G. (1982), p. 152
[45] Cf. Tunzelmann et al. (2008), p. 467

sectors.[46] Spur calls this innovation-orientated classification of technology types.[47] This classification is directly linked to technology life cycle models.[48] The life cycle of a technology gives information on ideal-typical courses of development of technologies. Life cycles represent a generalization of concrete, time-dependent observations of technology developments.[49] There are several theoretical models on the life cycle of technologies such as Gartner's Hype Cycle Model, Ansoff's technology live cycle model, and so on, which will not be explained in detail in this thesis.[50] A more expedient classification of technologies, as mentioned previously, is the innovation-oriented classification of technology types. There are three different technology types: pacemaker technologies, key technologies, and basic technologies.

Pacemaker technologies

Pacemaker technologies are at a very early stage of development.[51] Those are potential key technologies of tomorrow if they reach the stage of a product or process innovation.[52] Due to its stage of development, only a few companies have implemented these technologies. They have a big potential for creating high value for businesses, but also constitute a potential risk factor.[53] The expectations on sustainable impact pacemaker technologies on market potentials are significant because of their strategic importance for competition.[54]

Key technologies

Key technologies develop from the previously mentioned pacemaker technologies.[55] They ensure and possibly facilitate market growth, as they have been introduced as innovations.[56] Key technologies create a sustainable impact on strategic differentiation against competitors in a certain sector. Several leading companies have already implemented these technologies. Thus, new competitors are attracted by the prejudices of the technologies.[57] The investments for the development of these technologies are still high (in relation to basic technologies) due to its potential extension to other application areas.[58]

[46] Cf. Heubach, D. (2008), p. 35
[47] Cf. Spur, G. (1998), p. 87
[48] Cf. Heubach, D. (2008), p. 35
[49] Cf. Schuh et al. (2011), p. 37
[50] Ibid., 38ff.
[51] Cf. Zimmermann, K. (2007), p. 2
[52] Cf. Perl, E. (2007), p. 50
[53] Cf. Gerybadze, A. (2004), p. 130f.
[54] Cf. Heubach, D. (2008), p. 35
[55] Cf. Zimmermann, K. (2007), p. 2
[56] Cf. Spur, G. (1998), p. 87
[57] Cf. Gerybadze, A. (2004), p. 130f.
[58] Cf. Perl, E. (2007), p. 50

Basic technologies

Basic technologies are tested, approved, and already standardized in one or more industry sectors. Their potential to grow and their potential for change are bailed out.[59] These technology types, on the one hand, are responsible for business success, but, on the other hand, are not able to ensure competitive advantage anymore.[60] The use of fundamental technologies in certain sectors is a requirement for playing a considerable role in that area of activity.[61]

Another important technology type, which does not fit into the above-mentioned classical model from literature, but has a significant importance, is called cross-sectional technology. Cross-sectional technologies are also called enabling or platform technologies. They are characterized by their application in different areas, as they are the basis for other technologies.[62] Information and communication technology (ICT) and microelectronics are good examples of cross-functional technologies, as they penetrate most economic and social areas.[63] The innovation-oriented technology types, previously mentioned, can also be perceived as cross-sectional technologies if they are used in different application areas.

2.1.4 Technology and innovation management as strategic cornerstones

Technologies have a significant influence on the competitiveness of companies. On the one hand, technologies represent new strategic company resources with considerable development opportunities. On the other hand, new technologies threaten those companies, which base their strategic position of success on outdated technologies. Hence, companies are forced to develop new, customer-oriented technologies rapidly, implement and substitute them on time.[64] Wolfrum (1995) claims that technologies might be perceived as a weapon for competition, as unique technological knowledge increasingly takes in a leading position for establishing the new potential for company success.[65] An appropriate technology management nowadays is pivotal to secure the existence of an enterprise in the long term. By definition, technology management can be described as the management of technological knowledge and proficiency. It includes the provision, storage, and utilization of knowledge particularly in the field of natural sciences and engineering.[66] Technology management represents a subsection of the

[59] Cf. Perl, E. (2007), p. 49
[60] Cf. Spur, G. (1998), p. 87
[61] Cf. Gerybadze, A. (2004), p. 130f
[62] Cf. Heubach, D. (2008), p. 36
[63] Cf. Zahn, E. (1995), p. 4
[64] Cf. Klapper et al. (2011), p. 6
[65] Cf. Wolfrum, B. (1995), p. 244
[66] Cf. Perl, E. (2007), p. 25

company management in terms of content.[67] Essential tasks of the technology management process are planning, organization, and controlling of technological knowledge.[68] A special focus in the literature is set on the planning aspect of technology management, where the planning activities shall ensure the strengthening of a company's market position.[69] Due to an increased responsibility and importance of the technology administration in a business's organizational structure, the development of technology strategies gains remarkable attention.[70] A technology strategy describes how a company should use its technologies to stay competitive on the market.[71] The technology strategy defines technological objectives and gives hints to target the achievements. It denotes the usage of technologies according to their purpose and targeted technological level of performance. Moreover, the technology strategy determines at which dates technologies are implemented and where to procure them.[72] Gerybatze (2004) emphasizes the consistent integration of a technology strategy into the corporate strategy of a company. He adds that successful technology-oriented companies show a particularly high "fit" between corporate strategy, business strategy, and technology strategy.[73] To justify the process-oriented character of technology management there have been six essential, interconnected activities identified, which can be seen as the ground pillars of a wide-ranging technology management: Technology foresight, technology planning, technology development, technology utilization, technology protection, and technology evaluation.[74] The content of this thesis will be located among two activities of the technology management process, responsively **technology foresight** and **technology evaluation,** due to the intention of identifying technology potential and deriving recommendations for action for technology supplier and technology user. Both activities will be briefly described in the next section.

In some fundamental literature on theory of technologies the authors claim, that technology management is to a certain degree an integrative part of innovation management. In fact, both areas of management have a cross-sectional character with overlaps but still are independent fields.[75] Technology management goes beyond innovation management, as its management competencies include the whole life cycle of technology. Innovation management only deals with new developments and

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[67] Cf. Klapper et al. (2011), p. 6
[68] Cf. Perl, E. (2007), p. 25
[69] Cf. Klapper et al. (2011), p. 5
[70] Cf. Schulte-Gehrmann et al. (2011), p. 55
[71] Cf. Wolfrum, B. (1995), p. 246f.
[72] Cf. Schulte-Gehrmann et al. (2011), p. 55
[73] Cf. Gerybadze, A. (2004), p. 108
[74] Cf. Schuh et al. (2011), p. 15
[75] Cf. Zahn, E. (1995), p. 15

introductions of technologies.[76] The field of activity of innovation management is oriented on product development processes and market launch processes.[77] The Organization for Economic Co-operation and Development (OECD) defines the term innovation as "[…] first-time application of science and technology in a completely new way combined with economic success."[78] The term innovation in turn has to be distinguished from the term invention. An invention is a "realization of solutions for scientific-technical problems from the perspective of a company". Inventions are the result of all research and development activities.[79] Brockhoff tries to bring both terms together by concluding, if a new invention has the potential for business success, investments in preparation of production, and marketing activities have to be set up to launch the invention on the market. In the case of a successful market launch, the invention turns into a product or process innovation.[80] The innovation management process, in most cases, is initiated by either a "technology push" or "market pull". A "technology push innovation" is a supply-induced innovation, which is often developed through new technological developments, whereas a "market pull innovation" mostly is triggered by market-induced elements such as new customer needs.[81] Gerpott makes a proper definition of the relation between technology and innovation management, which will be underlying for this thesis. Gerpott uses the term strategic technology and innovation management (TIM) to describe a technology-oriented innovation management, which mostly includes the above-mentioned tasks of the technology management process such as planning, organization, and controlling of new technologies.[82] In particular, the following three main goals are targeted:[83]

- **Provision** of new technologies for the company
- **Realization** of technologies in new products and/or new processes
- **Utilization** of new technologies, which were elaborated by the company or other, external institutions

The main objective of TIM is to realize a technology position of the company, which lasts a) for a longer period and b) significantly ensures or improves the strategic location of the success of the enterprise.

[76] Cf. Zahn, E. (1995), p. 15
[77] Cf. Klapper et al. (2011), p. 8
[78] Cf. Spur, G. (1998), p. 161
[79] Cf. Gerpott, T. J. (2005), p. 25
[80] Cf. Brockhoff, K. (1994), p. 28
[81] Cf. Gerpott, T. J. (2005), p. 51f.
[82] Ibid., p. 57
[83] Ibid.
Accentuations were made by the author.

2.1.5 Technology foresight and technology evaluation

Successful companies often have a technological basis, which enables them to defend their sustainable competitive advantage. This technological basis is subject to constant change due to environmental circumstances, such as new customer needs or innovative technology developments. [84] Hence, companies are constantly well advised to monitor the market for emerging technology developments to protect or expand their strategic position on the market. This monitoring is the central idea of an extensive technology foresight. The main objective of technology foresight is to identify and evaluate systematically relevant technologies to elaborate essential information concerning future decision-making processes of the management on technology strategy (see chapter 2.1.3).[85] Through an extensive technology foresight, a company shall at an early stage get the chance (a) to build up own competencies on "highly promising" technologies, and (b) to procure technology-based assets from technology suppliers and integrate them into existing business processes.[86] In technology foresight, the foundations for decisions on future technological innovation activities of a company are laid. Thus, the quality and the type of information is vital. They include (among others): [87]

- Potential for further developments of technologies
- Limitations of existing technologies
- Relations of technologies and possible substations
- Expected disruptions in the development of technologies (technological discontinuities)

Next to the identification of potential technologies, especially the evaluation of new technologies plays an essential role.[88] Technology evaluation has within the technology management process a cross-functional character. It serves in different decision-making processes as an important source of information. Decisions, which require a technology evaluation, occur in all of the six above-mentioned basic technology management activities (see chapter 2.1.3).[89]

The term technology evaluation has to be distinguished from technology assessment[90]. The process of technology assessment analyzes indirect effects of new technologies on all areas of social life. Technology evaluation, as previously mentioned, generally makes

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[84] Cf. Wellensiek et al. (2011), p. 89
[85] Ibid, p. 90
[86] Cf. Gerpott, T. J. (2005), p. 101f.
[87] Ibid. and cf. Haag et al. (2011), p. 313
[88] Cf. Haag et al. (2011), p. 313
[89] Ibid., p. 309
[90] For the sake of avoiding misunderstandings the German translation of the term will be provided – Technology assessment = Technologiefolgenabschätzung

statements on the impacts of a technology for a certain company.[91] There are several methods for the execution of technology evaluation, which are determined in VDI Guideline 3780[92] such as cost-benefit assessment, Delphi- Method and risk analysis just to name a few.[93] For a successful technology evaluation the chosen evaluation criteria, which depend on the goals of the assessment, play a significant role. In literature several criteria, such as costs, quality, flexibility, and so forth can be found.[94] Heubach in his dissertation, which was a big inspiration for the methodical approach of the present thesis, uses technological functions as evaluation criteria to examine the technological relevance of nanotechnologies in product planning processes.[95] The usefulness of functions as evaluation criteria for technologies in the context of Industry 4.0 will be explained in chapter 2.2.2.

The illustration in figure 2 puts important theoretical concepts of the previous chapters into the contextual relationship of this thesis.

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91 Cf. Haag et al. (2011), p. 311
92 VDI Guidelines are rules for the procedure of scientific-technical processes made by the Association of German Engineers (Verein Deutscher Ingenieure, VDI)
93 Cf. Kröll, M. (2007), p. 39
94 Ibid. 56ff.
95 Cf. Heubach, D. (2008), p. 42

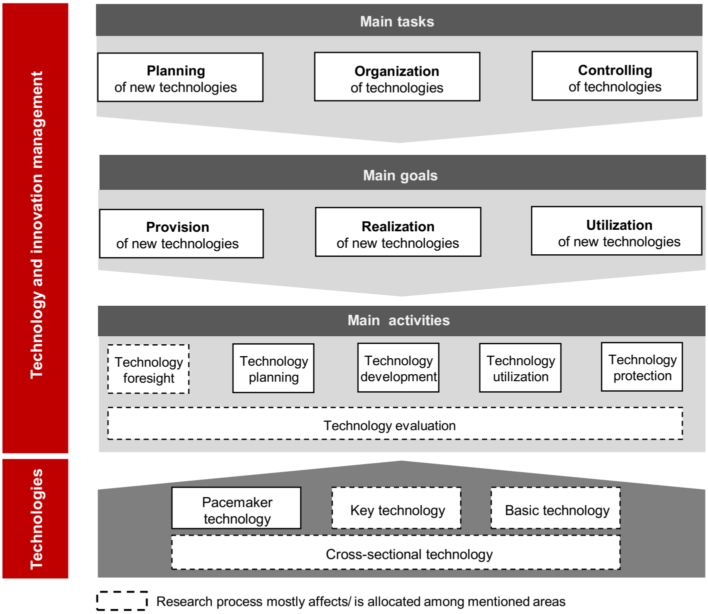

Figure 2: Technology and innovation management
(Source: Own representation)

2.2 Function aspect of technologies

In this section, initially the term function will be explained and afterwards its importance concerning the identification of technology potential will be emphasized.

2.2.1 Function definition

In literature, there are many definitions of the term "function".

Concerning technology, a very accurate definition, and distinction is made by Spur (1998). He describes the function of a technology and a technological system as *"[…] explicit, reproducible relationship between input and output parameters."*[96] The standard DIN EN 1325 defines technological function more output-oriented as the *"[…] effect of a product or its components."* The term "effect" in this context has to be understood as "procedure" or as "result" of an effect of a component.[97] The guideline VDI 2803 refers to DIN standard 66910, where the term function is defined in a relation to value

[96] Cf. Spur, G. (1998), p. 29
[97] Cf. DIN EN 1325, p. 10

analysis.[98] VDI 2803 defines an important module of value analysis, namely the function analysis. Function analysis tries to identify functions of products, processes, and services in the theory of design, to achieve optimal performance. It analyzes the effects, purposes, and concepts of objects. Moreover, VDI 2803 standardizes the methodical procedure of a function analysis and defines central terms such as function classes, and function types. Just to name a few, there are primary functions, overall functions, and undesirable functions.[99] In VDI 2803, the formulation of functions is also standardized. According to this, functions have to be described with a noun and a verb, e.g. “transmit torque.”[100] In this thesis, such a formulation will be refused, as the technologies of Industry 4.0 are quite unexplored, and a too detailed disassembly of functions would not be expedient, especially for the empirical study.

According to DIN EN standard 1325, a difference is made between user-oriented functions and product-oriented functions of a product, process, or service. User-oriented functions are defined as an effect, which is expected of the product to fulfill a part of the user’s needs. Whereas product-oriented functions affect a component of a product or rather the effect between the elements of a product to fulfill the previously mentioned user-oriented functions.[101] By referring to DIN EN 1325, Heubach emphasizes the constitution of technologies as **target-means combinations**. He names user-oriented functions “purpose function” and product-oriented functions “system functions”. Hence, system functions of technology (means) cause effects on a product to fulfill a “purpose function” of a product (target).[102]

2.2.2 Function as evaluation criteria for technology potential

Numerous measures to evaluate technology potential can be found in literature. Spur (1998) states that technology potential can be assessed by its capacity for innovations, especially based on apparent, future-oriented factors.[103] He references Kornwachs, which claims that the potential of technology might be evaluated based on its actual and possible application areas, expected further development, chances for novel solutions to existing problems, and range of improvements for work and life quality. Tshirky understands technology potential as a socio-technical subsystem of a company, which includes the company related potential users of all available technologies and their

[98] Cf. VDI 2803, p. 2
[99] Ibid.
For more detailed information on function classes and function types see: VDI 2803.
[100] Ibid.
[101] Cf. DIN EN 1325, p. 10
[102] Cf. Heubach, D. (2008), p. 91.
[103] Cf. Spur, G. (1998), p. 90f.

synergies.[104] These approaches are not sufficient for the present research initiative. A more sophisticated and detailed approach for the evaluation of technology potential is the investigation of the capabilities of a technology in terms of material, energy, and information capability.[105] This approach reflects the use of technological functions as evaluation criteria, as a function by its output-oriented definition is a measure of the “effect” of a component (see previous chapter). This approach does initially imply a trade-off between the expressions of individual needs and the technological possibilities of solving a problem (user-oriented vs. product-oriented functions). Both sides seem to speak different technological “languages”, though using the same terms.[106] A clarification of how the application of the principle of functions as evaluation criteria for technology potential, in particular, is useful will be explained briefly.

Technological systems only make sense if they work. Consequently, the guiding principle for the development of technologies has to be targeted on functionality.[107] From the perspective of a customer, technological functionality means “usability” of the system and its effects. Whereas, on the other hand, functionality from the viewpoint of an engineer or a developer means “feasibility” or “technical efficiency as the output of a possible increase in performance”. Hence, the technological function has two main tasks:[108]

(1) The concept of function serves as value assignment. The value of technology results from its technological efficiency and innovation potential. Thus, a technology, which improves a process and so forth using a certain function, has a particular value.

(2) The concept of function tries to solve the aforementioned problem of “different languages.” It serves as a translator between user-oriented and product-oriented perceptions of technology.

Pfeiffer claims that “thinking in functions” is especially important for the technology foresight process (see chapter 2.1.5) of the technology management, as it shows the lowest level of complexity by reducing a problem solely to its potential function.[109]
Within the scope of this thesis, both tasks of technological functions have a special meaning. On the one hand, this thesis tries to examine the value of technologies for end-to-end digital integration based on functions (value assignment). On the contrary, the effects of technologies have to be “translated” to make the technologies accessible to

104 Cf. Spur, G. (1998), p. 90f.
105 Ibid., p. 94
106 Cf. Heubach, D. (2008), p. 91
107 Cf. Spur, G. (1998), p. 29
108 Cf. Heubach, D. (2008), p. 42
109 Ibid., p. 91

the experts of the empirical study. Furthermore, only product-oriented functions (system functions) will be explored within the analysis. User-oriented functions will play a minor role, as they will be identified to show the practical relevance of the identified technologies in production logistics in Chapter 6. There are three basic elements of the identified function, which constitute technology potential in this thesis:

(1) Influence on end-to-end digital integration
(2) Practical relevance
(3) Market readiness

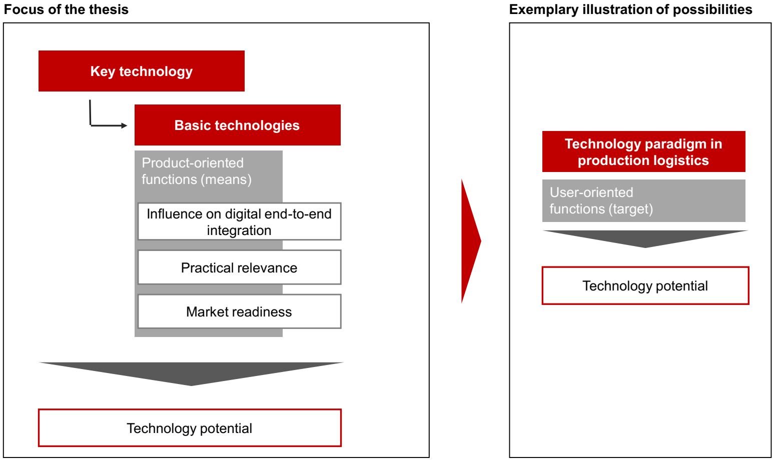

Figure 3: Underlying approach of technology potential identification
(Source: Own representation)

2.3 Production logistics

This section completes the theoretical background information. The terms "logistics" and "production logistics" will be defined, described based on their main tasks, and brought into the context of this thesis' research initiative.

2.3.1 Logistics definition

The origin of the term "logistics" can be traced back to the 19th century, where it was defined as planning of supply and troop movements in military terms. The French term "logis" means troop accommodation and is said to be the root of the term "logistics." A relation to the Greek term "logos" (logic), which often is mentioned as the origin of the term "logistics," is questionable.[110] The importance of logistics, as a management discipline, was never as big as it is currently. Baumgarten, which is an essential pioneer and forerunner of the massive development of logistics, states that 30 years ago no one would believe that the logistics of the 21st century is a significant factor for competition and simultaneously a meaningful source of hope for German economy.[111] Logistics for a long time was simply reduced to the classical triad of the functions storage, handling, and transport. This picture has changed over the years. Today's logistics is faced with enormous social responsibility, e.g. in dealing with questions of demographic change, climate change, sustainability, and resource efficiency.[112] Even though nowadays no one can deny the practical relevance of logistics, the basic understanding of the scientific discipline logistics differs considerably. This variance probably arouses due to its multifaceted nature and diversity of topics.[113] A very basic, though appropriate understanding, defines logistics as "[…] the holistic planning, controlling, coordination, execution and monitoring of all company internal and company external flows of information and goods."[114] The same flow-oriented approach is used by the American Council of Supply Chain Management Professionals (CSCMP), which defines logistics as follows: "[…] the part of a supply chain process that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customers' requirements."[115] Hence, the major characterization of logistics in comparison to other scientific disciplines is its flow orientation, which is the first underlying principle. From this particular point of view, economic phenomenon and relationships are perceived as flows of objects, goods, people, and values through chains and networks of activities and processes.[116]

A second underlying principle of logistics is its holistic view of activities, systems, and networks. The management and the execution of individual storage or transport processes, for example within a factory, has always been a primary task of logistics (see above). The particular way of the "logistical thinking" is the consideration of several processes simultaneously as "one flow" in a network and its coordination concerning the overall objectives of the system.[117] Pfohl (2010) calls this phenomenon "system theoretical approach" of logistics, in short "systems thinking." He claims that the

[110] Cf. Arnold et al. (2008), p. 3
[111] Cf. Baumgarten, H. (2008), p. 13
[112] Cf. Hompel, M. ten et al. (2014), p. 3
[113] Cf. Delfmann et al. (2011), p. 1
[114] Cf. Hompel, M. ten et al. (2014), p. 6
[115] Cf. Pfohl, H.-C. (2004), p. 3
[116] Cf. Clausen, U.; Geiger, C. (2013), p. 4
[117] Cf. Arnold et al. (2008), p. 3f.

questions to be considered are not “which” logistics tasks are addressed but rather “how” logistics tasks are tackled. “Systems thinking” has its origin in biology, where it defines a certain number of interconnected elements. The main characteristic of “systems thinking” is the finding that it is not possible to explain the entire system by explaining its parts. To define the complete possibilities of a system, the relationships of the systems’ elements also have to be considered.[118]

2.3.2 Production logistics as phase-specific subsystem of logistics

A distinction of logistics systems is necessary concerning different challenges and problems, which arise in the planning and design process of logistics systems. Pfohl (2010) points out two different approaches, which are based on the scope and the point of view (aggregation level) on logistics systems. From the perspective of the aggregation standards of a logistics system, it is differentiated between macro, micro, and meta level.[119] Logistics systems on the macro level have macroeconomic dimensions, such as the entire freight transport (road, rail, and sea), whereas micro logistic systems consequently have micro economic dimensions. They deal with logistic systems of, for example, hospitals, military, and individual companies.[120] Meta logistics is in between both previous mentioned logistic systems.[121] A more functional distinction, which meets the requirements of the above-mentioned flow orientation of logistics, is the phase-specific view on in logistics subsystems and its flow of goods (see figure 4).[122]

118 Cf. Pfohl, H.-C. (2010), p. 25f.
119 Ibid., p. 14ff.
120 Cf. Wannenwetsch, H. (2014), p. 14
121 Cf. Pfohl, H.-C. (2010), p. 14ff.
122 Ibid., p. 16f.

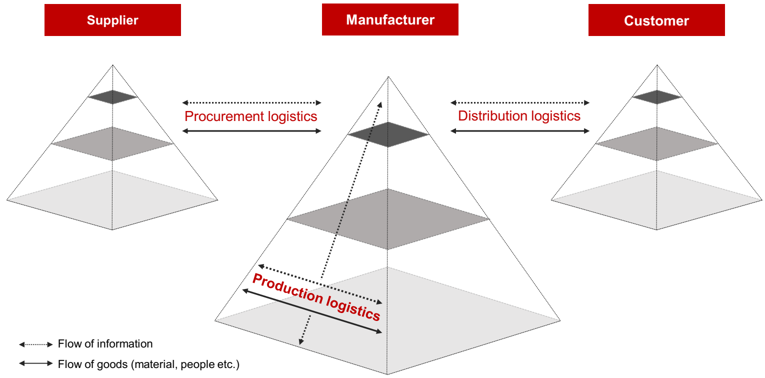

Figure 4: Phase-specific view on logistic subsystems
(Source: Own representation based on Schuh et al. (2011))

The flow of goods starts with the procurement and the following flow of raw materials, auxiliary materials, and consumables from the supplier network. This phase is called *procurement logistics* and handles the availability of manufacturing goods, which are not produced by the company itself. It includes all necessary activities to supply the production side with all needed production inputs.[123] The second phase, where all the delivered and partially stored raw materials, components, semi-finished goods, and finished products are transported to either manufacturing stations or internal warehouses is called *production logistics*.[124] In literature, the term *intra logistics* is often used as a synonym for production logistics.[125] The third phase is characterized by flows of semi-finished goods and finished products either to distribution warehouses or directly to the customer. This phase is called *distribution logistics*.[126] Within the scope of this thesis, the focal point is set on the production logistics of a company and its main tasks, which will be explained as follows.

2.3.3 Main tasks

The manufacturing industry follows logistics, not the other way round, as it was the practice in recent centuries (see chapter 2.3.1).[127] This ongoing change of logistics, as management discipline, has especially consequences for the tasks in production

[123] Cf. Schuh et al. (2011), p. 13
[124] Cf. Pfohl, H.-C. (2010), p. 17
[125] Cf. Arnold et al. (2008), p. 5
[126] Cf. Pfohl, H.-C. (2010), p. 17
Pfohl mentions a fourth phase, *disposal logistics,* which is not explained explicitly here, as it’s not a part of the value creation process and therefore has no considerable meaning in the context of this thesis.
[127] Cf. Auffermann et al. (2014), p. 6

logistics. The core task of logistics can be formulated very appropriately using the so-called Six-R-Rule of logistics, which simultaneously describes the main goals of logistics. According to this, Logistics handles the supply of the right *product*, in the right *quantity*, with the right *quality* at the right *time*, at the right *place* and to the right *costs*. To fulfill the "six-Rs", the execution of main logistics processes such as transport, handling, storage, commissioning, and packaging has to be guaranteed.[128] An adequate execution of logistics process cannot be assured without prior planning and control processes. This leads to the planning functions of production logistics, which by many authors are seen as vital competencies of production logistics. Production logistics deals next to execution with "[…] the planning, control and monitoring of production and internal transport, handling, and warehousing processes."[129] Pawellek emphasizes the flow-oriented perspective on the tasks, where the production inputs are moved "[…] from a raw material warehouse through phases of production processes into a finished goods warehouse."[130] According to Arnold, these tasks can be assigned to the phase-specific view on logistics subsystems (see previous Chapter) to create a planning matrix. Within this matrix, the activities can be systemized by three different levels of planning, namely the long-term strategic, the middle-term operative, and the short-term operative planning of internal processes (see below figure 5). In terms of production logistics, especially the middle-term operative and short-term operative planning have a certain relevance. Initiated by customer orders, the middle-term planning involves the following processes:[131]

Production planning process:

- Production program planning
- Quantity planning (material requirements planning)
- Planning of deadlines and capacities

The short-term operative planning sometimes is used as synonym for production control and consists of the following functions:[132]

Production control:

- Release of customer orders

[128] Cf. Schuh et al. (2011), p. 8f. and cf. Delfmann et al. (2011), p. 3
[129] Cf. Arnold et al. (2008), p. 181
[130] Cf. Pawellek, G. (2004), p. 417
[131] More detailed components such as *lead time scheduling* are not mentioned explicitly for the sake of clarity.
[132] Cf. Arnold et al. (2008), p. 324
More detailed components such as the *forming of order sequences* are not mentioned explicitly for the sake of clarity.

- Monitoring of customer orders

The operational execution of production logistics mainly includes five different core activities, which will be briefly described in the following, as they have a particular relevance for this thesis.

The **transport,** as the term already suggests, mainly handles covering of distances of goods. It moves the goods to either warehouses or manufacturing workplaces. Each transportation system consist of transportation means, a good, which has to be transported and a transport system.[133] **Handling** processes deal with the loading and unloading of transportation means and storages as well as with the collection and sorting of goods. Handling processes connect external and internal flows of material and different transport sections.[134] The **storage** has the function of covering time. Goods are stored and taken out of the warehouse by various storage strategies. The storage itself is no activity, only the processes to fulfill the storage. **Commissioning** means compiling stored articles for a customer order, consisting of one or more different goods. The customer of commissioning order can be either a final customer or a working place in production, which needs stored material.[135] The **packaging** has an auxiliary function.[136] It serves as protection for the aforementioned activities, namely transport, handling, storage, and commissioning of goods. The packaging is defined by the designing process of packaging materials and actual packaging process.[137]

	Long-term strategic planning	Middle-term operative planning	Short-term operative planning	Operational execution
Planning horizon	Several years	6-18 months	1-3 months	Hours, days
Activities	▪ Production depth and outsourcing strategies ▪ Investments in production assets and storage facilities ▪ Layout of production and warehouse ▪ …	Production planning ▪ Production program planning ▪ Quantity planning (material requirements planning) ▪ Planning of deadlines and capacities	Production control ▪ Release of customer order ▪ Monitoring of customer order	▪ Transport ▪ Handling ▪ Storage ▪ Commissioning ▪ Packaging

Figure 5: Production logistics planning activities
(Source: Own representation based on Arnold (2008))

[133] Cf. Pfohl, H.-C. (2010), p. 149f.
[134] Cf. Arnold et al. (2008), p. 7
[135] Ibid.
[136] Cf. Pfohl, H.-C. (2010), p. 134
[137] Ibid, p. 137ff.

The above-mentioned activities are mostly combined with technical logistics systems, which support the activities by guaranteeing:

(1) The flow of information between different planning and control activities as various data is needed to fulfill process on different levels
(2) The flow of materials between the various manufacturing locations

The systems, connection between these systems, and resulting challenges of these systems in contextual relationship to the topic of this thesis will be explained in the next Chapter, as they are the core of the underlying research initiative.

3 The concept Industry 4.0

In this chapter, the German concept Industry 4.0 will be described in detail. Initially, the drivers of the concept will be explained followed by a description of what is meant by the concept, its potential and similar, international approaches. Afterwards, the meaning of an end-to-end digital integration within a Smart Factory will be described explicitly.

3.1 Drivers of Industry 4.0

The first section of this chapter deals with drivers of the fourth industrial revolution. It initially presents market-driven factors, new technological possibilities, and Germany's position as a manufacturing power.

3.1.1 Changing market demands

Manufacturing industry is subject to considerable, structural changes due to global megatrends. Westkämper (2013) points out several ongoing developments, which will substantially influence the entire manufacturing environment.[138]

Individualization

An obvious development in recent years is the increased demand for individualized products. The consideration of customer wishes in many industries such as textile, furniture, personal computer, cars, and machines, has become to a certain extent standard. The benefits of traditional industrial mass production based on automation, economies of scale, and knowledge through experience, which have been the fundament of international operating manufacturing companies for a long time, seem to disappear smoothly. [139] Nowadays, more and more attention is paid to the customer's desires and individual needs, which lets the degree of personalized products increase significantly. Due to the changing customer demands, it is fundamental to adapt manufacturing processes and technologies to this development.[140] Already implemented concepts such as mass customization and versatile serial production based on modular systems could preserve the benefits of standardized manufacturing systems. The industry will have to cope with a nearly complete integration of customers into their processes in the mid and long term.[141] The quantities per model and per version will continue to sink in future.[142] An entirely new level of work approaches will occur, in which the customer will simultaneously be the producer ("prosumer"). The customer expresses

[138] Cf. Westkämper, E. (2013), p. 7f.
[139] Cf. BMWi (2010), p.12
[140] Cf. Kelker, O. (2011), p. 5
[141] Cf. BMWi (2010), p.12
[142] Cf. Kelker, O. (2011), p. 5

C.J. Bartodziej, *The Concept Industry 4.0*, BestMasters,
DOI 10.1007/978-3-658-16502-4_3

wishes, makes suggestions for product innovations ("open innovation"), and actively takes part in the development and manufacturing processes.[143]

Volatility

Dealing with short cycled, fluctuating markets is a crucial factor to stay competitive, as the developments after the global economic crisis have shown. Spath et al. (2013) emphasize the term volatility, as the dictate of the moment.[144] Volatility by definition means *"likely to change suddenly and unexpectedly […]*."[145] From the perspective of macro and microeconomic developments, volatility describes the relative size of fluctuations of prices, share prices, and exchange rates, interest rates as well as entire markets within a certain time horizon, though volatility is not a measure of the direction of fluctuations.[146] Volatile markets with fluctuations in demands affect particularly the manufacturing industry due to different sources of volatility. Short-term company-specific effects, seasonal fluctuations, product life cycle, and other market fluctuations are underlying factors, which influence the volatility of producing companies, especially in sales.[147] Volatility is perceived as the main driver for a paradigm shift in manufacturing, as it requires more flexible and adaptable structures, processes, products, and systems in manufacturing. Future companies will have to invest in flexibility and adaptability, as the classical instruments will not be able to master volatility any longer.[148]

Energy and resource efficiency

A sustainable and secure supply of raw materials and energy is vital for the competitiveness of an industry. The future development of the energy sector will be determined by ambitious climate goals, worldwide growth of population, and global rise in prosperity.[149] In the long term, this combination will lead to an exponential increase in demand for energy and mineral raw materials. According to expert estimations, the overall demand will double until 2050.[150] By mentioning this, it gets clear that the way society is using natural resources has to change radically. Otherwise, fossil fuels will be depleted soon. Manufacturing industry, without a doubt, has particular responsibility in terms of energy efficiency and resource conservation, as it has by far the highest final and primary energy consumption concerning other industries.[151] Kagermann et al.

143 Cf. BMWi (2010), p.12
144 Cf. Spath et al. (2013), p. 21
145 Cf. Cambridge Dictionaries Online (2015)
146 Cf. Spath et al. (2013), p. 70
147 Ibid.
148 Cf. Kelker, O. (2011), p. 4
Flexibility and adaptability will be discussed in detail in Chapter 3.3.1
149 Cf. BMWi (2010), p.12
150 Cf. Bauernhansl, T. (2014), p. 11f.
151 Ibid.

address the threats to environment and security of supply next to the costs the high-energy consumption cause. Resource productivity and resource efficiency should be included in the strategic goals of each manufacturing company.[152] Any waste in production, which, for example, is caused by over production, quality issues, or unused potential for optimization, has economic and social consequences.[153]

3.1.2 New technological possibilities for the future of manufacturing

The German Federal Ministry of Economic Affairs and Energy[154], in a report from 2010, presents different fields of technological engagements in which research has to be promoted to strengthen Germany's position as leading manufacturing power. The progress of these so-called "enabling technologies" will determine the potentials in different areas. Modern manufacturing technologies, optical technologies, microsystems technology, nanotechnology, biotechnology, electronics, new materials, and geo-technology are perceived to realize this potential.[155] A more detailed approach in terms of the aforementioned manufacturing technologies is made by Bauer et al. (2013). They identified five technology fields, which are considered to be in the sphere of influence in the concept Industry 4.0. For them embedded systems, smart objects, CPS, the concept of a Smart Factory, robust networks, cloud computing, and IT-security constitute the technological cornerstones for future production and success.[156] Sendler (2013) and Kagermann et al. (2013) mention Cyber-Physical-Systems in one breath along with the Internet of Things and Services. Both authors state that these technologies will be the basis for the evolution from the third to the fourth phase of industrialization.[157] Regarding the Internet of Things and Services, Spath et al. (2013) claim that the current developments in Social Media, Social Web, and Web 2.0 will enter manufacturing environment the same way they entered private households.[158] According to Kelker (2011), there are two further technology developments, which will shape the future of manufacturing - Big Data and Human Machine Interaction. Big Data technologies analyze and process the extensive volume of data, multimodal Human-machine interfaces such as touch displays and gesture recognition will allow employees to build up wholly new levels of communication and interaction in a manufacturing

[152] Cf. Kagermann et al. (2013), p. 7
Resource productivity means to strive for the highest possible output quantity with given means (resources), whereas resource efficiency means to strive for the lowest possible resource usage while fulfilling a predetermined production quantity (output).
[153] Cf. Kelker, O. (2011), p. 7

[155] Cf. BMWi (2010), p. 11f.
[156] Cf. Bauer et al. (2014), p. 18ff.
[157] Cf. Kagermann et al. (2013), p. 17 and cf. Sendler, U. (. (2013), p. 8ff.
Both, CPS and the Internet of Things and Services, are in the center of this research initiative and will be explained in detail in the next chapter.
[158] Cf. Spath et al. (2013), p. 44

environment.[159] Capgemini Consulting has developed their own Industry 4.0 framework to explain future developments in manufacturing. In their eyes, the seven following core technology enablers will affect the manufacturing sector positively: Cloud computing, advanced analytics, mobile computing, machine-to-machine communication, advanced robotics, community platforms, and 3D printing.[160] A report on Industry 4.0 and the digitalization of the manufacturing sector recently was published by the strategic consultancy McKinsey&Company. This report sets its focus on four clusters of disruptive technologies, which will have a significant impact on manufacturing within the next ten years, when citing the authors. According to McKinsey&Company, the upcoming technologies can be systemized as follow:[161]

- Data, computational power, and connectivity (e.g. wireless networks)
- Analytics and Intelligence (e.g. artificial intelligence of objects)
- Human-machine interaction (e.g. augmented reality (AR) solutions)
- Digital-to-physical conversion (e.g. 3D printing)

The ongoing developments and elaborations on future technologies in manufacturing are the driving force for research initiatives in this area. In this section, it becomes very clear that nearly every market player (private and public) yields to define, explain, and create a “big picture” of manufacturing future in order to keep the pace with others. This has certain legitimacy. Although, a deeper understanding of the concepts, ideas, and technologies as well as its relations is needed, especially for the implementation in practice.

3.1.3 Germany’s position as manufacturing power

In comparison to other member states of the European Union (EU), Germany generates a major share of European industrial value creation. With 31% in 2012, Germany had the highest share of the EU followed at some distance by Italy with a share of 13%, France and Great Britain with 10%.[162] Even on international level, Germany is in good economic shape regarding manufacturing. The average, worldwide share of manufacturing industry in gross value added (GDP) in the last decade was always around 17%, which is very high compared to other sectors. Germany right after China, the United States (US) and Japan is the fourth biggest industrialized nation. However, the maximum share of manufacturing industry mostly cannot be found in classical industrialized nations but more in emerging economies (BRIC states), especially in

[159] Cf. Kelker, O. (2011), p. 8f.
[160] Cf. Capgemini Consulting GmbH (2014), p. 20ff.
[161] Cf. McKinsey & Company (2015), p. 11ff.
[162] Cf. Eurostat (2013), p. 1

Southeast Asia. The average share of manufacturing industry in Southeast Asian countries accounts for approx. 25%, where China makes a big contribution with more than 30% in the last decade. Among all classical industrialized nations, it has the highest share of manufacturing industry in GDP (see the comparison in figure 6[163]).[164] Germany has one of the most competitive manufacturing industries in the world and is a global leader in the manufacturing equipment sector. This competitiveness is in no small measure due to Germany's specialization in research, development, and production of innovative manufacturing technologies and the management of complex industrial processes. Germany's strong machinery and plant manufacturing industry, its globally significant level of IT competencies and its know-how in embedded systems and automation engineering mean that it is extremely well placed to develop its position as a leader in the manufacturing engineering industry. [165]

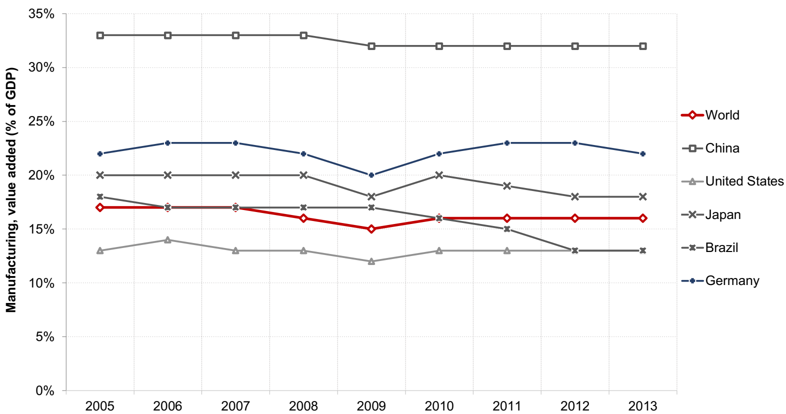

Figure 6: Comparison of share of manufacturing industry in GDP
(Source: Own representation based on Worldbank (2015))

In 2014, Germany's share of manufacturing industry increased to 25.9%[166] of total GDP, which means that every second workplace was either directly or indirectly related to manufacturing. The development of the last two decades can be seen as a result, since the early 1990s, Germany has yielded a share of manufacturing industry in GDP with

[163] Cf. BDI (2015)
[164] Cf. Worldbank (2015)
[165] Cf. Kagermann et al. (2013), p. 17f.
[166] Cf. Federal Statistical Office (2015), p. 1, also note: Manufacturing industry does not include construction industry.

always more than 25%. Even though the world financial crisis in 2008 brought an economic downturn (first time under 20%), Germany's economy recovered very fast until 2011.[167]

3.2 Main idea of Industry 4.0

The following section has a huge explanatory function, as it describes the main idea of the concept Industry 4.0 and its essential components. Firstly, the historical origination of the term Industry 4.0 will be described followed by a definition, core elements, the economic potential and a distinction of similar, international approaches.

3.2.1 Phases of industrial developments

The process of industrialization began with the introduction of mechanical manufacturing equipment at the end of the 18th century.[168] Driven by the development of the steam engine by James Watt, machines and engines revolutionized the way goods were made. The transformation from an agricultural to an industrial society was introduced. The first industrial revolution made a tremendous contribution to the decrease of famine catastrophes in industrial-oriented countries and, simultaneously, to the resulting development of a population explosion.[169] This transformation was followed by a second industrial revolution that began around the turn of the 20th century and involved electrically powered mass production of goods based on the division of labor.[170] This revolution was predominantly coined by organizational changes such as the implementation of Henry Ford's assembly line and the scientific management procedures based on Frederic W. Taylor, better known as Taylorism. The large-scale industrial manufacturing (mass production) raised and especially proceeded in chemical and electronics industry as well as in mechanical engineering and automotive industry.[171] This development was replaced by the third industrial revolution that started during the early 1970s and has continued right up to the present day. This revolution is characterized by the implementation of electronics and information technology to achieve increased automation of manufacturing processes, as machines gradually took over and replace a high proportion of labor work. Thus, an essential result of this transformation had socio-economic and socio-cultural effects, namely a high degree of

[167] Cf. Bauernhansl, T. (2014), p. 7f.
[168] Cf. Kagermann et al. (2013), p. 17f.
[169] Cf. Bauernhansl, T. (2014), p. 5
[170] Cf. Kagermann et al. (2013), p. 17f.
[171] Cf. Bauernhansl, T. (2014), p. 6

rationalization in the companies. On the other hand, the productivity of manufacturing processes increased due to an introduction of versatile serial production.[172]

The third revolution is still present, but it is smoothly transforming into a new age of industrialization – the fourth industrial revolution.

3.2.2 Industry 4.0 - The fourth industrial revolution

There is considerable evidence that the fourth industrial revolution is smoothly taking over. It is often discussed, whether the term "revolution" is justified for the ongoing change. Some people state that a more reasonable definition would be "evolution", as the transformation will take several decades and the main elements, which constitute this transformation process, already exist and only will be developed further. Whereas other people claim that, the term "revolution" is justified, as the transformation has similar characteristics to an epochal transformation due to a most probable paradigm shift in manufacturing. [173] One definition is certain – it will be an (r)evolution towards digitalization. Jacobi and Landherr (2011) highlight the ongoing social change of an industrialized society to a post-industrialized knowledge-based, service-oriented, information-based society, which is designated to be a "digital" revolution.[174]

Due to these fundamental changes, the German government introduced the "strategic initiative" Industry 4.0 in January 2011. It was launched by the Communication Promoters Group of the Industry-Science Research Alliance (FU). Its initial implementation recommendations were formulated by the Industry 4.0 Working Group between January and October 2012 under the coordination of the National Academy of Science and Engineering (Acatech).[175] Since 2006, the German government has been pursuing a High-Tech Strategy for the coordination of research and innovation initiatives in Germany with the objective to secure Germany's strong competitive position through technological innovation. Its release is known as High Tech Strategy 2020 and focuses on five priority areas: climate/energy, health/food, mobility, security, and communication. A first, very vague definition of the term Industry 4.0 was made by the FU in 2011. It defines Industry 4.0 as "[…] the fourth industrial revolution, a new level of organization and control of whole value chains over the entire lifecycle of products. This cycle includes the fulfillment of individualized customer requirements and extents itself from idea, real order, development, and manufacturing, delivery to the customer and the recycling

[172] Cf. Bauernhansl, T. (2014), p. 6
[173] Cf. Sendler, U. (2013), p. 7
[174] Cf. Jacobi, H.-F.; Landherr, M. (2013), p. 41f.
Within this thesis, the more common term "revolution" will be used.
[175] Cf. Kagermann et al. (2013), p. 81

process with the involved services. The basis for the development is formed by the availability of all necessary information in real-time through interconnection of all instances, which are involved in value creation as well as through the ability to derive the best possible value stream based on the resulting data. Through the connection of people, objects and systems, dynamic, real-time optimized, self-organizing, cross-company value networks will evolve, which can be optimized based on different criteria such as costs, availability and resource efficiency."[176] As this definition on a first glance seems to be overloaded, a more precise definition was made by Acatech in 2013. It perceives Industry 4.0 as

"[…] the technical integration of CPS into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes. This will have implications for value creation, business models, downstream services and work organization."[177]

Currently, nearly every technology-related company tries to find an own explanation of what actually constitutes the concept Industry 4.0 (see chapter 3.1.2). This makes it even harder, especially for companies, to cope with the complexity of this topic, as people often seem to interpret essential parts completely differently. A very helpful move towards a unique conception of Industry 4.0 was recently made by Hermann et al. (2015) using a literature review. The literature review identified four key components of Industry 4.0, namely Cyber-Physical Systems, Internet of Things, Internet of Services, and Smart Factory. Technologies like machine-to-machine communication and Smart Products are not considered to be independent Industry 4.0 components, as machine-to-machine communication is an enabler of the Internet of Things, and Smart Products are a subcomponent of CPS. The authors perceive big data and cloud computing as data services, which utilize generated data in Industry 4.0 implementations, but not as independent Industry 4.0 components.[178]

This is enough evidence to set the focus on Kagermann's definition of Industry 4.0 due to its technology orientation, which was confirmed by Hermann's elaborations. It emphasizes the symbioses of the key technologies CPS, the Internet of Things and Services, as the fundament of all developments and consequences, which are related to the concept Industry 4.0. It furthermore sets the model of the Smart Factory in the center of all further reflections in that context.

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[176] Plattform Industry 4.0 (2014), p. 1
[177] Kagermann et al. (2013), p. 18
[178] Cf. Hermann et al. (2015), p. 7

3.2.3 Central features of the concept

Industry 4.0 should not be approached as a closed system but rather should be considered as one essential part out of several key areas. In a smart, interconnected world based on the Internet of Things and Services the economic key sectors will be transformed into smart infrastructures and constellations. This transformation leads to the emergence of smart grids and smart buildings in the field of energy supply, smart and sustainable mobility and logistics solutions, smart health, and so forth. Hence, Industry 4.0 should be thought, implemented, and lived in an interdisciplinary manner and close cooperation with the other key areas (see figure 7).[179] Within this smart ecosystem, Industry 4.0 is the manifestation of the "smart thinking" approach in manufacturing environments.

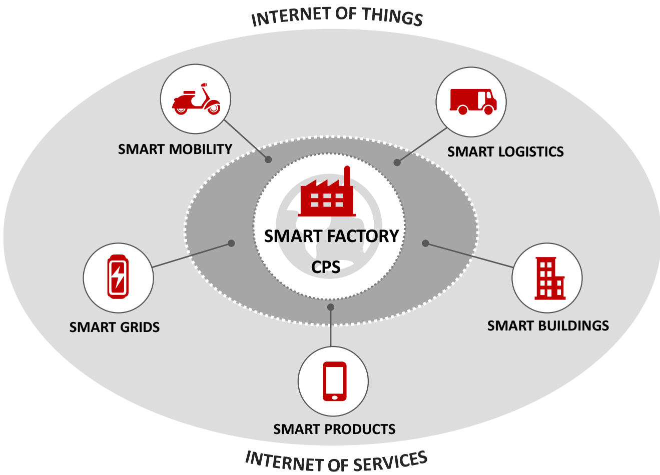

Figure 7: Smart Factory in the center of the concept Industry 4.0
(Source: Own representation based on Kagermann et al. (2013))

In the center of Industry 4.0, the concept of a Smart Factory constitutes a key feature. According to experts, the Smart Factory has several novel characteristics, which makes enables companies to cope with complexity and unexpected disruptions as well as to manufacture products more efficiently. In a Smart Factory, people, machines, and resources communicate with each other as naturally as in a social network.[180] For the

[179] Cf. Kagermann et al. (2013), p. 23
[180] Ibid.
The concept of a Smart Factory will be described in detail in the next section.

elaboration and implementation of Industry 4.0 solutions, the focus is set on the three following overarching features and simultaneously prioritizes areas for action:[181]

<u>Horizontal integration through value networks</u>
Integration of various IT systems used in the different stages of the manufacturing and business planning processes that involve an exchange of materials, energy, and information both within a company (e.g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks).

<u>End-to-end digital integration of engineering across the entire value chain</u>
Appropriate IT systems, which can provide end-to-end support to the entire value chain, from product development to manufacturing system engineering, production, and services. A holistic systems engineering approach is required, which includes different technical disciplines.

<u>Vertical integration and networked manufacturing systems</u>
Integration of various IT systems at the different hierarchical levels within a company (e.g. actuator and sensor, control, production management, manufacturing and execution, and corporate planning levels) in order to deliver an end-to-end solution. The object of reflection is the Smart Factory, where those systems and technologies come into use.

These three key features of the transformation process will have far-reaching implications not only on economic levels in form of new business opportunities and novel business models but also in terms of new social infrastructures, organizational structures, and legal concerns. The spectrum of tasks for employees, the required qualification, and the innovative interaction in form of extensive human-machine cooperation will have a significant impact on future socio-economic work systems. New emerging, interconnected value chains will change traditional business models and organizations from competitive market players to cooperating competitors ("coopetition").[182]

3.2.4 Economic potential

The potential of the fourth industrial revolution for the entire manufacturing environment is huge. Kagermann et al. (2013) depict eight fundamental changes, which are likely to be enabled by the transformation process:[183]

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[181] Cf. Kagermann et al. (2013), p. 23
[182] Cf. Plattform Industry 4.0 (2015), p. 4f.
[183] Cf. Kagermann et al. (2013), p. 19f.

- Meeting individual customer requirements
- Flexibility
- Optimized decision-taking
- Resource productivity and efficiency
- Creating value opportunities through new services
- Responding to demographic change in the workplace
- Work-Life-Balance
- A high-wage economy that is still competitive

These changes correlate strongly with cost-reduction potentials. Even though at this moment an estimation of reliable cost-saving potentials is difficult to make, the possible interventions and optimizations into running operations along the entire value chain will have huge impact on capital costs, energy cost, and labor costs.[184] According to a study by the German Federal Association for Information Technology, Telecommunications and New Media (BITKOM e.V.) the German GDP will annually increase by 1.7% from 2013 to 2025 based on the implementation of Industry 4.0 technologies in six selected industry sectors. In total, the potential would sum up to a cumulated increase in GDP of 23% (78.77 billion Euros) from 2013 to 2025 (see figure 8).[185] The strategic consultancy The Boston Consulting Group (BCG) even predicts an additional annual increase of 30 billion Euros per year, which amounts to 1.1% of current GDP. In particular, a huge productivity increase in mechanical and plant engineering is perceived as very likely due to the technical interconnection of a supplier and manufacturer.[186]

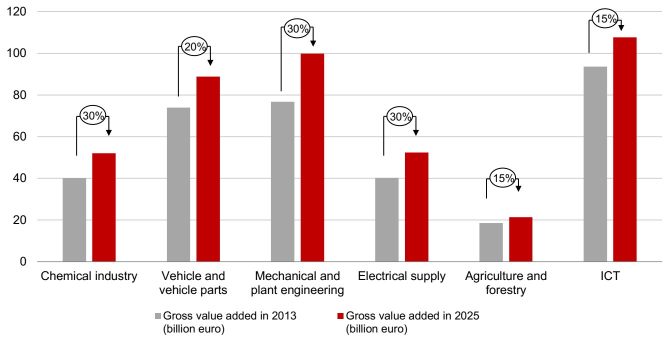

Figure 8: Economic potential of Industry 4.0 in selected sectors
(Source: Own representation based on Bauer et al. (2014))

[184] Cf. Heng, S. (2014), p. 7
[185] Cf. Bauer et al. (2014), p. 35f.
[186] Cf. The Boston Consulting Group (2014), p. 1

With reference to a study of PricewaterhouseCoopers (PWC)/Strategy& in which 235 German companies were questioned for their future Industry 4.0 investments, the results show that in average the companies will invest 3.3% of annual turnover in Industry 4.0 solutions in the next five years. Herein, the investments are allocated among all-important key areas within the value chain (see figure 9).[187]

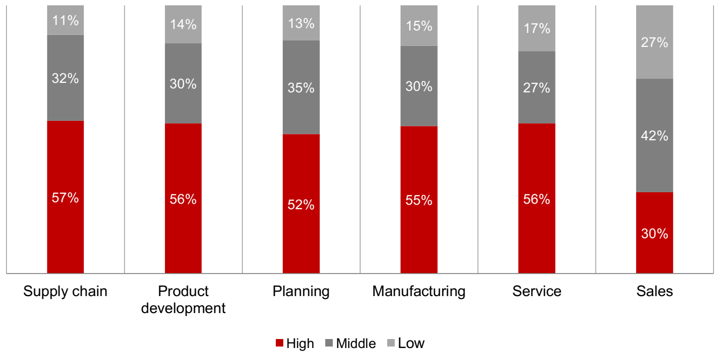

Figure 9: Planned investments in Industry 4.0 solutions in different areas

(Source: Own representation based on PwC Strategy& GmbH (2014))

3.2.5 Similar, international approaches

Besides Germany, other states are also pursuing the modernization of industrial processes. A variety of different terms around the world is used to describe the German phenomenon Industry 4.0. Just to name a few, the terms "Smart Production", "Smart Manufacturing", "Integrated Industry"[188], or "Connected Industry"[189] are used in Europe, China and the US to refer specifically to digital networking of production in order to create smart manufacturing systems.[190] Some of the terms are invented by private institutions, and others are forced by public initiatives of governments.

A very famous private movement, which is perceived as German counterpart of the Industry 4.0 initiative and is heavily pursuing towards the worldwide leadership in terms

[187] Cf. PwC Strategy& GmbH (2014), p. 13
[188] Guiding principle of the German Hannover Messe in 2014, which stands for an interconnection of all areas in manufacturing.
[189] Innovation cluster of Bosch AG, which deals in particular with issues in interconnected industrial production.
[190] Cf. Kagermann et al. (2013), p. 71

of technical standards and new, digital business solutions, is the US Industrial Internet Consortium (IIC). The IIC is an open membership, nonprofit organization that catalyzes, coordinates the priorities, and enables technologies of industry, academia, and the government around the Industrial Internet.[191] They defined the term Industrial Internet as "[…] the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes."[192] The international company General Electric (GE), as a founder of the IIC, constitutes three major pillars of the Industrial Internet: Intelligent machines, advanced analytics, and people at work. [193] GE estimates that the Industrial Internet could add $10 - $15 trillion to the global GDP over the next 20 years.[194]

Another public driven initiative to accelerate the industrial transformation was recently set up by the Chinese government. China will implement the "Made in China 2025 (中国制造2025)" strategy alongside an "Internet Plus" plan, based on innovation, smart technology, the mobile Internet, cloud computing, big data, and the Internet of Things to accelerate the transformation of China from a big manufacturing power to a strong, smart manufacturing power. Inspired by the German Industry 4.0 (工业4.0) and its High-Tech Strategy (see chapter 3.2.2), the Chinese government promotes the digitalization of the industry to strengthen its worldwide position as an industrial power.[195]

3.3 End-to-end digital integration within a Smart Factory

In this section the Smart Factory, a major part of the concept Industry 4.0 will be explained using elements, which might constitute essential pillars of it. Hereby, a special focus is set on end-to-end digital integration within a Smart Factory.

3.3.1 Flexibility and adaptability as main objectives

Individualization, volatility, energy, and resource efficiency are predominant drivers in terms of changing market demands and concerning an increase of manufacturing complexity (see chapter 3.1.1). Mastering these new challenges requires new manufacturing approaches concerning organizational structures, processes, and technologies. The importance of (production) logistics within the context of flexible and adaptable systems becomes obvious. In a Smart Factory, inflexible and rigid systems

[191] Cf. Industrial Internet Consortium (IIC) (2014), p. 1
[192] Ibid. Note: Experts in the US speak of a third industrial revolution. This is due to the fact that they either include the second Industrial Revolution (the establishment of mechanical mass production) as part of the first or that they are not counting the third transformation of industry, as it is resulting from the automation of manufacturing processes as a genuine revolution in its own right (cf. Kagermann et al. (2013), p. 71)
[193] Cf. Evans, P.; Annunziata, M. (2012), p. 3f.
[194] Cf. Industrial Internet Consortium (IIC) (2014), p. 1
[195] Cf. Wübbeke, J.; Conrad, B. (2015), p. 6

are completely in the wrong place.[196] From the perspective of designing and developing production and logistics systems, it is vital to have a closer look at what in fact makes a difference between flexible and adaptable systems, as both are seen as key factors for success and often are used as synonyms. [197] Flexibility by definition means the ability to react to changes within a predetermined scope of requirements (corridor of action) time and cost effectively.[198] Concerning production logistics, flexibility involves the adaptation of structures and processes to changes on a tactical level by referring to the joint interaction of employees, machines, production systems, and value creation networks.[199] In a future of volatile market demand, it is questionable if the mentioned corridor of action will be sufficient to tackle dynamic changes. On the other hand, it would be economically unreasonable to enlarge the corridors of actions to master the major of unpredictable changes. [200] This is the point where adaptable systems will become essential. Adaptability exceeds flexibility as it represents the potential of a system:

(1) to react to changes beyond the predetermined corridors of action
(2) to proactively react on changes[201]

In context of logistics, Adaptability means the ability of a material flow system to adapt to new circumstances by being expendable and variable.[202] Processes and systems can be changed and modified by simply rebuilding, for example, a machine to produce different products.[203] According to Nyhuis (2008), there are six different enablers to enhance adaptability: [204]

- scalability
- mobility
- modularity
- universality
- compatibility
- neutrality

Figure 10 shows the relationship between flexibility and adaptability for a better comprehension.

[196] Cf. Günthner,et al. (2014), p. 298f.
[197] Cf. Steegmüller, D.; Zürn, M. (2014), p. 103
[198] Cf. Sommer-Dittrich, T. (2010), p. 73
[199] Cf. Plattform Industry 4.0 (2014), p. 13
[200] Ibid.
[201] Cf. Nyhuis, P. (2008), p. 24
[202] Cf. Günthner et al. (2014), p. 298f.
[203] Cf. Plattform Industry 4.0 (2014), p. 13

[204] Cf. Nyhuis, P. (2008), p. 28f.

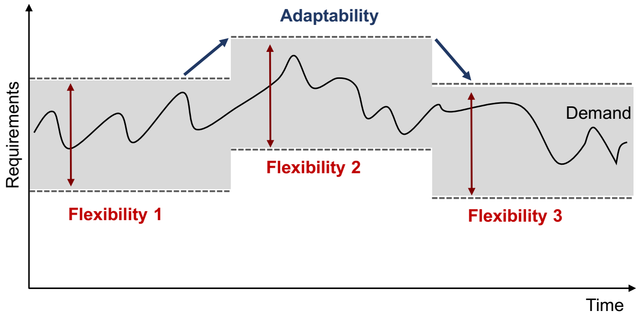

Figure 10: Distinction flexibility vs. adaptability
(Source: Own representation based on Nyhuis (2008))

3.3.2 Current technological solutions in production logistics

Classical production logistics tasks and activities (see chapter 2.3.3) are mostly combined with technological systems, which support the fulfillment in different dimensions. These technological systems predominantly have their origin in the field of information technology, automation technology, and microelectronics. On operational execution level, technologies classically were implemented to guarantee a smooth flow of materials, whereas a consistent flow of information has to be ensured by different technological systems on production planning and control level. Against the background of the research initiative, it is vital to get an overview of currently existing technologies in the field of production logistics according to its tasks and activities.

In manufacturing, there is one superior production planning and control system, which has a centralized, hierarchical, and pyramid-shaped structure. This structure has its origin in automation technology and predominantly controls architectures. The application areas in classical manufacturing industry on different levels of the automation pyramid (also called layers) are defined in DIN ISO standard 62264.[205] Planning and control tasks are allocated vertically to different hierarchical levels on this pyramid. Explicit distinctions in competencies in terms of control activities on each level are formulated prior to the implementation of those systems.[206] Concerning the tactical planning and operational execution of production logistics processes, in particular, material flow control systems constitute a major part of the automation pyramid. These systems are used to handle rises in complexity due to a high degree of automation. They

[205] Cf. Schöning, H. (2014), p. 543
[206] Cf. Schlick et al. (2014), p. 73

perfectly adapt to the aforementioned pyramid-shaped structure. [207] The main task of a material flow control system, namely the execution of transport orders, is subdivided into different activities that are more granular such as definition of transport rules (e.g. FIFO), ensuring optimal utilization of physical transport resources (e.g. conveyor systems), visualization to interact with employees (e.g. fault detection), collection of data and transmission of other systems (e.g. ERP, MES), recording, storage, and provision of data (e.g. key performance indicators) .[208]

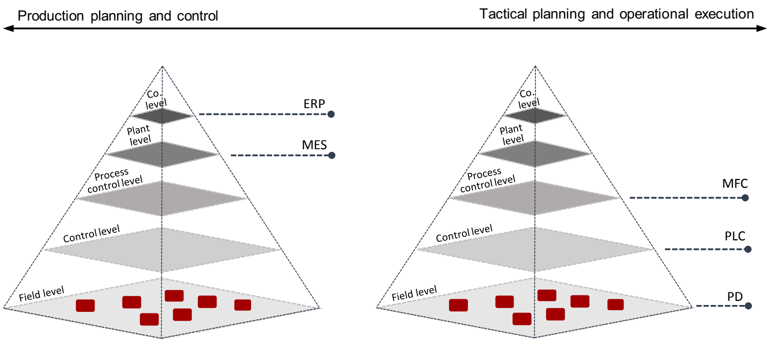

Figure 11: Automation pyramid vs. material flow control system
(Source: Own representation based on VDI (2013))

These activities are supported by minor, individual systems. The interaction of these individual systems and its allocation to the planning and control processes is illustrated in figure 11. The systems and its primary functions will be described as follows.

<u>Company level – Enterprise Resource Planning (ERP)</u>

ERP systems are the core of industrial information systems and, thus, form the backbone of a business. They can be used in a single factory as well as go beyond a factory's boundary. ERP systems fully support the order fulfillment.[209] They are perceived as integrated software solutions, which consist of several modules such as procurement, logistics, plant maintenance, finance, controlling, and production planning and execution and are connected based on a centralized database.[210] ERP systems can be seen as an

[207] Cf. Nieke, C. (2010), p. 17
[208] Ibid., p. 15ff.
[209] Cf. Schuh, G.; Stich, V. (2013), p. 277
[210] Cf. Schmidt et al. (2014), p. 282

extension and further development of production planning systems (PPS) above. Classical PPS mainly support industrial production processes in terms of planning and control, ERP systems go beyond these activities, as they also cover administrative issues, e.g. accounting and human resources.[211] In practice, people frequently use both terms as synonyms.[212] ERP tools, concerning the planning horizon, allow handling future requirements of more than six months (e.g. quantity planning, see chapter 2.3.3).

Plant level – Manufacturing Execution Systems (MES)

MES are allocated on plant level and, thus, have tight interdependencies with ERP systems on company level. MES are indispensable for modern, integrated management of manufacturing, as they are perceived as an important add-on for ERP solutions in terms of detail planning processes. If ERP systems reach their limitations concerning granularity of planning processes, MES takes over the roughly scheduled manufacturing orders from ERP, initiates the finite planning and control, and gives feedback of order processing and completion. MES consists of several hardware and software components, which optimize the entire manufacturing process.[213] Through the proximity to actual manufacturing processes, MES are able to collect and analyze data and, thus, influence all relevant parameters for control of manufacturing with the objective to create a complete and real-time virtual copy of manufacturing processes.[214] MES is an operational control system, which is directly connected to technical control systems in production logistics (esp. MFC) and, thus, is an essential part of the automation pyramid.[215]

Process level (production logistics) – Material flow computer (MFC)

The process control is the highest level of the material flow system. As technology on this level of control often a material flow computer is used, which has the function of guaranteeing a seamless flow of information to coordinate the entire movement of materials within a factory.[216] Its primary task consists of transport execution and transport administration. Transport execution means fulfilling and coordinating transport orders, whereas transport administration includes monitoring, commissioning, and coordination of transports.[217] The MFC, thus, directly communicates with the technical control level, which executes the transport orders. It also is connected to the systems of the next

[211] Cf. Schuh, G.; Stich, V. (2013), p. 260
[212] Cf. Schmidt et al. (2014), p. 287
[213] Ibid.
[214] Cf. Arnold et al. (2008), p. 343
[215] Cf. Schuh, G.; Stich, V. (2013), p. 260
[216] Cf. Nieke, C. (2010), p. 18
[217] Cf. Arnold et al. (2008), p. 815ff.

higher level (MES), where it receives transport orders.[218] Consequently, the function can be seen as an important mediator between planning, control, and execution.

Operational Execution

The operational execution of production logistics processes, in general, is divided into two sections, the technical control (control level) and the execution by itself (field level). The technical control does support the execution by means of ensuring the actual flow of information, and the execution by itself guarantees the flow of materials. [219]

Control level - Programmable logic controller (PLC)

At this level, the technical control of field devices is managed. This is the level, where information technology directly influences (controls) mechanic processes. This level is not to be confused with the plant level, which also assumes control.[220] This level processes signals of field devices and controls the corresponding actuators (e.g. initiates the movement of conveyor technology). It often is equipped, due to its proximity to the actual manufacturing process, with human-machine-interfaces (HMI). In terms of hardware construction, PLCs are developed in form of a classical PLC-device, an Industrial PC or the form of a Soft-PLC.[221] At this level, the real-time capability of technological systems is crucial. Therefore, sensors and actuators of field devices are mainly connected to PLCs through either field bus systems or Ethernet. The higher one climbs the automation pyramid, the less the requirements for real-time capability.[222]

Field level – Field devices (FD)

According to the automation pyramid, in literature the level is named operating data acquisition, which means all necessary data is collected at the place of origin.[223] At this level, there are many technological alternatives in production logistics, which enable the collection of data and transmission to systems of a higher level.

In essence, transport systems in production logistics predominantly include conveyor technology. It serves as the underlying technology for the primary function of transport systems, namely the transport.[224] The transport process itself can be subdivided into: merging, buffering (in terms of storage), separating, and distributing.[225] For the transport

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[218] Cf. Nieke, C. (2010), p. 18
[219] The previously mentioned packaging and handling processes and its supporting technological systems will not be explained in detail, as they predominantly have auxiliary functions or are indirectly included in the other processes (transport, storage and commissioning, see chapter 2.3.3).
[220] Cf. Schlick et al. (2014), p. 73
[221] Cf. Nieke, C. (2010), p. 25
[222] Cf. Libert, S.; Roidl, M. (2010), p.49
[223] Cf. Schmidt, C. et al. (2014), p. 287
[224] Cf. Pfohl, H.-C. (2010), p. 134
[225] Cf. Arnold et al. (2008), p. 614

process, there are two different types of conveyor technology, which are classified based on the continuity of the transportation procedure: continuous conveyor and non-continuous conveyor. Famous examples of continuous conveying technologies in current production logistics systems are belt conveyor, roll conveyors, suspension chain conveyor, circular conveyor, and slat conveyor. Non-continuous conveyor systems mostly have more degrees of freedom than continuous systems and, thus, more flexible. Famous examples are rack feeder, storage and retrieval machine, crane, electric monorail conveyor, forklift, and automated guided vehicles (AGVs).[226] AGVs are mostly perceived as complete transportation systems, as they usually have their guiding and control systems, which either are actively or passively inductive.[227] Usually, conveying systems were centrally installed. Centralized approaches are proven and, thus, a major part of implemented industrial conveyor systems. The main component of this approach is the fixed installed control cabinet, which is connected via cables to all other necessary components.

Storage systems can be systemized based on different storage types. The storage types can be structured by their function, building height, stored goods or loading devices (storing devices), and loading aids.[228] The choice of appropriate loading aids, which enable and guarantee a stable flow of materials, already, has to be considered within the process of storage development. There are several technical devices, which either autonomously fulfill loading and unloading processes or support the employee doing so. Stacker cranes are one possibility to fully automate storage systems. Lifting devices are another opportunity for handling goods in the storage zone. Various alternatives are existing on how these technologies can be implemented in storage systems. It also depends on the circumstances and the purpose of a particular application.[229]

The core process of commissioning is the “picking,” the removal, and the hand-over of a predefined quantity of goods. This process is executed either by an employee or by an automated system. The whole process, therefore, can be subdivided into the four following components: Supply of commissioned goods (statically or dynamically), movement of picker (one-dimensional or two-dimensional), removal of the goods (manually or mechanically), and hand-over of goods (centralized or decentralized). [230]
There are several technical alternatives, which can support these processes. The technical design possibilities of the commissioning technology are very diverse. Arnold

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[226] Cf. Arnold et al. (2008), p. 613ff.
[227] Ibid., p. 639f.
[228] Ibid., p. 646
[229] Cf. Arnold et al. (2008), p. 636
[230] Cf. Arnold et al. (2008), p. 676

states that there are 16 different basic systems that exist referring to VDI standard 3590. The possibility of combining those systems with the various picking processes allows the emergence of more than 1000 commissioning systems, of which 50 are used in practice.[231] The control of the commissioning process is managed by either an employee or warehouse management. The needed information for the “picking” process can be provided either on a paper-based picking list or by optical and acoustical displays (pick-by-voice and pick-by-light).

3.3.3 Dissolution of classical automation pyramid

In the concept Industry 4.0, a focus is set on vertical integration within a factory (see chapter 3.2.3). The previously mentioned technological systems in production logistics often are not appropriately interconnected, which leads to media disruptions and, thus, hampers a consistent flow of information among different hierarchy levels of the automation pyramid. These problems especially exist at the interfaces of real world processes (field level – control level), where data has to be firstly collected and then processed in systems at higher levels.[232] According to a study in 2013, the feedback of data into IT-Systems in small and medium-sized enterprises (SMEs) is to 57% executed manually as written answer. This insufficient data quality has negative consequences on planning and control processes, as it is the backbone of IT-systems at these levels.[233] Hence, it is essential to ensure end-to-end digital integration from field devices across different levels right up to the ERP systems (company level).[234] In a novel, entirely interconnected world, each field device is able to initiate an exchange of data to different levels.[235] This interconnectedness will lead to dissolution of classical, rigid hierarchies of the automation pyramid (see figure 12).

[231] Cf. Arnold et al. (2008), p. 676
[232] Cf. Schoch, T.; Strasser, M. (2003), p. 9 and cf. Bürger, T.; Tragl, K. (2014), p. 561
[233] Cf. Schuh et al. (2014), p. 278f.
[234] Cf. Kagermann et al. (2013), p. 36
[235] Cf. Hoppe, S. (2014), p. 331

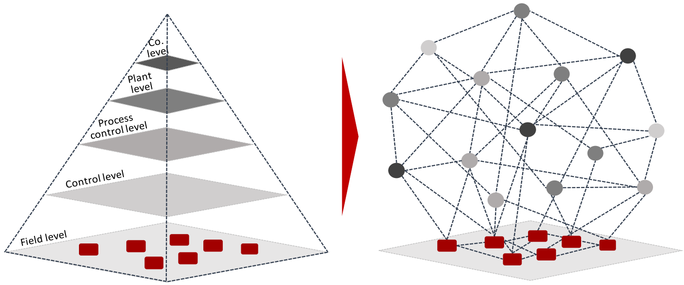

Figure 12: Dissolution of classical automation pyramid
(Source: Own representation based on VDI (2013))

Having mentioned this, the extent of a possible dissolution is uncertain. Experts state that dissolution of hierarchical structures is not to be confused with superfluousness of classical systems. The functions of an ERP system, for example, will still be essential but may be used in a different, more decentralized manner.[236] For a common understanding of the further research procedure, the term end-to-end digital integration of technological systems in a Smart Factory is defined as follows:

End-to-end digital integration implies a real-time capable, consistent, when required bidirectional flow of data and information between all involved, heterarchical structured technological systems within a Smart Factory in order to ensure planning, control, and execution of production logistics processes.

3.3.4 Paradigm shift in production logistics

Kuhn, who is seen as a pioneer of the theory of scientific paradigm (see chapter 2.1.2), describes the emergence of paradigm shifts using three examples. He states that the evolutionary findings of Nicolaus Copernicus (Heliocentrism), James Clerk Maxwell (Electromagnetic radiation), and Antoine Lavoirsier (Oxygen theory of combustion) all had the same fundamental of emergence. The new theories were first revealed after a common problem-solving ability obviously has failed. Kuhn interpreted the appearance of a new problem-solving theory as an immediate answer to a crisis.[237]

[236] Cf. Kleinemeier, M. (2014), p. 574
[237] Cf. Kuhn, T. S. (1976), p. 87

Apparently, in manufacturing currently, no one can speak of a crisis, but still the manufacturing environment is faced with entirely new challenges, which let the complexity of the entire manufacturing system rapidly increase and, thus, allow technologies, processes, and whole systems to become inefficient (see chapter 3.1.1 and chapter 3.1.3). The way value creation in manufacturing takes place nowadays, therefore, has to change. The design and organization of factories, as well as the way production factors (energy, material, labor, and assets), are used to significant change.[238] What does this so frequently predicted paradigm shift mean for production logistics? In a future-oriented production logistics, two features will set the tone: decentralization and autonomy.[239] Both characteristics are perceived as key for the highest level of productivity in future manufacturing systems.[240] To describe the emergence of the idea of decentralized, autonomous systems in production logistics, Hompel explains the following scenario: In 2008, a few engineers of Fraunhofer IML were thinking about the ideal system in production logistics. They all had an empty sheet of paper and a pencil. After an intensive discussion, only a sketch of a shelf at the lower edge of the sheet could be found. It was agreed that a shelf, as the main part of a warehouse, would be needed in future logistics. The remaining area was empty and indefinite. This emptiness exactly constitutes the central idea of decentralized and autonomous systems in production logistics, which can tackle future, volatile market demands and, thus, a higher complexity through a continuous adaptation to new circumstances.[241] In other words, classical, centralized structures in manufacturing will be replaced by decentralized, organized systems.[242] In literature, these approaches are specified as self-guiding and self-organizing characteristics of manufacturing systems.[243] This approach requires an aforementioned end-to-end integration digital of all involved technological systems in a Smart Factory. Traditional centralized coordination and control concepts, where collected data has to be matched and processed in a central control unit (e.g. MFC) and material and information flows are separated in future will be replaced. The emergence of either hybrid forms of centralized and decentralized elements or completely decentralized control systems will occur, depending on economic aspects.[244] Conventional IT systems, which are allocated on different hierarchy levels,

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[238] Cf. Bauernhansl, T. (2014), p. 11f.
[239] Cf. Günthner, W.; Hompel, M. ten (2010), p. V
[240] Cf. Bauernhansl, T. (2014), p. 33
[241] Cf. Hompel, M. ten; Henke, M. (2014), p. 615
[242] Cf. Günthner, W.; Hompel, M. ten (2010), p. V
[243] Cf. Windt, K. (2006), p. 1ff. and cf. Nopper, J. (2010), p. 230f.
A clear difference between "self-guidance" and "self-organization" will be discussed in chapter 4.5.2.
[244] Cf. Schuh, G.; Stich, V. (2013), p. 273

will become dissent to the new paradigm, as each system and subsystem have a coordination and control function for minor systems (see previous chapter).[245]

How will the control of, for example, a future conveyor system look like without a central coordinating unit? This question is where the autonomy of logistics objects comes into play. In a future production logistics systems, the equally operating systems execute all functions, which were previously managed by various IT systems on different hierarchy levels, by itself.[246] The Intelligent Objects will coordinate themselves and negotiate further tasks based on the model of the Internet, where router and switches transport data packages through a complex, evolving network.[247] This will be the origin of the Internet of Things in production logistics. Autonomous, intelligent logistics objects in this vision will get “eyes, ears, arms, and legs.” Through smart sensors and actuators, forms of artificial intelligence, nature-identical procedures, and machine-to-machine communication intelligent objects will cooperate with each other and, thus, control themselves through manufacturing processes.[248] Continuous, decentralized re-planning processes of transport routes in case of disturbances allow productivity increase, as there are no predefined control programs needed to be centrally adopted.[249] In some scenarios, experts even mention dissolution of the cycle-oriented production based on Taylor, where the cycle is the pulse of production. Within a flexible decentralized and autonomous production system, each Intelligent Object can search its optimal way to be produced, without being tied to a production cycle.[250] Consequently, fixed and highly complex systems will be replaced by highly flexible, adaptive, and extremely reactive systems and networks.

Technologies will enable the paradigm shift in manufacturing. In particular, the use of ICT systems, where service-oriented and agent-based architectures already exist, will allow an Internet of Things following the example of the common Internet.[251] In the field of ICT, the paradigm shift from centralized to decentralized systems also currently takes place and can serve as a role model, as the diffusion and implementation already are very advanced in different areas. Traditional, monolithic software systems, which have their standards, are replaced by open-standard systems. Classical software suites are replaced by concepts such as Software-as-a-Service, provided in the form of software

[245] Cf. Günthner et al. (2014), p. 299
[246] Ibid., p. 300f.
[247] Cf. Günthner, W.; Hompel, M. ten (2010), p. V
[248] Cf. Hompel, M. ten; Henke, M. (2014), p. 616
[249] Cf. Günthner et al. (2014), p. 299f.
[250] Cf. Bauernhansl, T. (2014), p. 20f.
[251] Cf. Günthner et al. (2010), p. 43

apps. Expansive license fees for huge software packages will become useless concerning the emergence of are pay-per-use-models for software.[252]

3.4 Conclusion

In the context of this thesis, Industry 4.0 is perceived as a concept founded by German institutions, organizations, and companies to ensure and strengthen Germany's strong competitive position in numerous industrial areas. Industry 4.0 is often used as a synonym for the fourth industrial revolution in Germany (see chapter 3.2.2). The full potential of the fourth industrial revolution for the entire manufacturing environment still is hard to figure out but is considered massive depending on the sector (see chapter 3.2.4). In various other states, there are similar approaches (especially in the US, the IIC), which also pursue the development of its industries. These approaches, on the one hand, can be perceived as a challenge, when the involved actors fight for the leading position in the world. On the contrary, it can be seen as a huge chance to develop new business models and cooperation based on the vision of "coopetition" (see chapter 3.2.5). The development of the concept is predominantly driven by new market demand such as individualization and volatility as well as by technological innovations (see chapter 3.2). The latter is the backbone of the concept. The integration of new technologies such as CPS and IoTS into industrial processes enables entirely new opportunities such as new business models and work organizations. Due to the wide-ranging components of the concept Industry 4.0 and their implications, within this thesis, the focus is solely set on the technologies, which enable the transformation of a fourth industrial revolution.[253] The concept has three central, overarching features, namely:

- Horizontal integration through value networks
- End-to-end digital integration of engineering across the entire value chain
- Vertical integration and networked manufacturing systems

The research initiative is bounded to technologies, which facilitate a vertical integration by means of an end-to-end digital integration within a Smart Factory and, thus, concentrates only on the third feature. An end-to-end digital integration of the technological systems can support planning, control, and execution of processes and, thus, can pursue a possible paradigm shift in production logistics (see chapter 3.2).

[252] Cf. Bauernhansl, T. (2014), p. 31

[253] The possible effects on other dimension are perceived as consequence of a technology implementation and will not be analyzed in detail. For example, there will not be investigated whether the use of a special technology will have negative influences on the employment rate.

4 Technologies and functions of the concept Industry 4.0

In this chapter, the technological foundation of Industry 4.0 will be explored by presenting key and basic technologies, their interaction, and the functions they offer in order to identify their influence on the afore defined end-to-end digital integration in production logistics.

4.1 The vision of Ubiquitous Computing

It is useful to explain the vision of ubiquitous computing to understand the development of the technological foundation of the concept Industry 4.0 [254].

In 1991 Mark Weiser, the former chief architect of the Palo Alto Research Center (PARC) at XEROX, developed the idea of a ubiquitous infrastructure for information and communication technology.[255] He envisages a change occurring from one centrally located infrastructure ("personal" computer) to a set of rather small, widely distributed devices. These devices will not even be perceived as computers or telecommunication devices. Instead, they will penetrate each area of social life; thus, will be seen as a natural part of daily activities.[256] He defined the underlying technology of these devices as "specialized elements of hardware and software, connected by wires, radio waves and infrared, (that) will be so ubiquitous that no one will notice their presence."[257] The current phase, where – to use Weiser's words – laptop machines, dynabooks, and "knowledge navigators" are essential parts of our daily lives, was predicted by Weiser as "only a transitional step towards achieving the real potential of information technology."[258] His definition nowadays still is rated as initial consideration for all resulting technological and socio-political developments in the field of "Smart Objects" and the Internet of Things.[259]

Weiser's vision very frequently is backed by an essential observation on the development of computing hardware, which is known as "Moore's law." This observation is named after Gordon E. Moore, co-founder of Intel Co., who described, back in 1965, that the number of transistors in a dense integrated circuit is approximately doubling every two years. This exponential improvement of the computing performance has dramatically enhanced the effect of digital electronics in nearly every segment of the

[254] Some authors use the terms "pervasive computing" and "ambient intelligence" as synonym to "ubiquitous computing".
[255] Cf. Botthof, A.; Bovenschulte, M. (2011), p. 2
[256] Cf. Meyer et al. (2009), p. 2
[257] Weiser, M. (1999), p. 3
[258] Ibid.
[259] Cf. Botthof, A.; Bovenschulte, M. (2011), p. 2

C.J. Bartodziej, *The Concept Industry 4.0*, BestMasters,
DOI 10.1007/978-3-658-16502-4_4

world economy. [260] Moore's law can be seen as important requirement and approach to making Weiser's vision of ubiquitous computing world come into practical life, as it is making his ubiquitous devices financially affordable.[261]

4.2 Cyber-Physical-Systems within the Internet of Things and Services

In this section the key technological concepts, namely Cyber-Physical-Systems and the Internet of Things and Services will be described in detail.

4.2.1 Cyber-Physical-Systems (CPS)

Initially, it has to be pointed out that behind the concept Industry 4.0 there is no such thing like one, new single "Industry 4.0 technology". [262] It is more the continuous progress of information and communication technology in combination with an exponential growth of computing, transmission, and storage capacity, which enables the emergence of increasingly powerful, interconnected new technological systems (see previous chapter) – these novel systems are called Cyber-Physical-Systems. [263]

These systems consist of some new and various already existing technologies.[264] In literature, one can find numerous explanations on the term CPS, but no accepted, explicit definition. In 2008, Lee defined CPS as:

"[…] integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa."[265]

The German Committee of Experts on Industry 4.0 defines CPS as follows:

"Systems, that directly links real (physical) objects and processes with information processing (virtual) objects and processes via open, partially global and always interconnected information networks."[266]

A third definition is made by Kagermann et al. (2013). According to them CPS:

"*[…] include embedded systems, production, logistics, engineering, coordination and management processes as well as internet services, which by courtesy of sensors directly collect physical data and by means of actuators influence physical procedures. These systems are interconnected via digital networks, use worldwide available data*

[260] Cf. Botthof, A.; Bovenschulte, M. (2011), p. 2
[261] Cf. Lucke et al. (2014), p. 12
[262] Cf. Bildstein, A.; Seidelmann, J. (2014), p. 581
[263] Cf. Geisberger, E.; Broy, M. (2012), p. 9
[264] Cf. Bildstein, A.; Seidelmann, J. (2014), p. 581
[265] Lee, E. A. (2008), p. 1
[266] Cf. German Committee of Experts VDI/VDE-GMA 7.21 „Industry 4.0“ (2014), p. 1

and services and are equipped with human-machine interfaces. Cyber-Physical-Systems are open socio-technical systems, which enable several novel functions, services and capabilities."[267]

Even though there is no sharp distinction of what constitutes a CPS, the main additional feature of these systems can very simply be seen in the direct linkage (smart combination) of "real" and "virtual" worlds.[268] Having mentioned that, the coupling of information processing components and physical objects in automation is not new and already existed since the 1970s. The essential innovation, which comes along with CPS, is the interconnection of objects and processes via open and global information networks – via the internet.[269] The main technological driver for the emergence of CPS has hardware and software based origins. On the one hand, the technological infrastructure consistent of embedded systems and high-performance sensors, actuators, and communication interfaces provides the inevitable hardware capacities.[270] Most of these embedded systems are currently closed "boxes" that do not expose the computing capability to the outside.[271] On the other hand, the use of the business web, integration platforms, and services based on cloud solutions opens entirely new business opportunities.[272] With special regards to the last two definitions, it is interesting to notice, that not only embodied objects (systems) can constitute CPS but rather intangibles such as operational and managerial processes as well. Due to this fact, CPS still constitute a rather abstract, theoretical concept more than a finished technology, which is ready to use and already has found its first applications and prototypes in industrial practice. Another characteristic, which can be used to describe a CPS and, simultaneously, shows the diverse dimensions of these systems, is the degree of decentralization of their structure and their spatial volume. By means of advanced micro-system technologies, a CPS can be placed on a single microchip including various sensors and a microprocessor for processing data. A bigger CPS can be constructed in the form of an entire machine tool, which can be in turn a part of an even greater CPS – a whole factory. An extreme manifestation of a CPS would be its allocation in a worldwide network, e.g. a worldwide operating company.[273] Both mentioned characteristics of CPS were elementary features of key technologies concerning technology classification models based on technology types (see chapter 2.1.3). Hence, CPS have to be designed according to the needs of the customer to reach its full potential. CPS have various

[267] Cf. Kagermann et al. (2013), p. 84
[268] Geisberger, E.; Broy, M. (2015), p. 7
[269] Cf. Bettenhausen, K. D.; Kowalewski, S. (2013), p. 2
[270] Cf. Geisberger, E.; Broy, M. (2012), p. 20
[271] Cf. Lee, E. A. (2008), p. 4
[272] Cf. Geisberger, E.; Broy, M. (2012), p. 20
[273] Cf. Lucke et al. (2014), p. 14

capabilities. Simply speaking, they can fulfill generic functions such as the search for appropriate services on the internet as well as application-specific functions, e.g. route optimization within a logistics network.[274] The development of these systems will go through several stages. Geisberger and Broy (2015) describe five essential dimensions of CPS, which build upon each other towards increasing openness, complexity, and smartness:[275]

(1) Merging of the physical and virtual worlds
(2) Systems of Systems with dynamically adaptive system boundaries
(3) Context-adaptive systems with autonomous systems; Active real-time control
(4) Cooperative systems with distributed and changing control
(5) Extensive human-system cooperation

At each of these stages, the design of CPS allows to develop various application-specific functions, which enable the resulting technologies to generate new benefits.[276]

4.2.2 Internet of Things and Services (IoTS)

The Internet of Things and Services is on closer inspection not a technology, but rather a concept. It has emerged, providing an umbrella for the increasing number of heterogeneous Smart Objects that are becoming part of our daily activities.[277] Windelband et al. (2010) highlight the aggregation of several technologies, which together, form the IoTS as they are mutually supporting each other. They refuse to consider the IoTS as independent technology.[278] While trying to understand the concept of IoTS, it is useful to separate the terms “Internet of Things (IoT)” and “Internet of Services (IoS)” and to have a closer look at both definitions. By definition, the IoT is the:

“[…] linkage of physical objects (things) with a virtual representation on the internet or a similar structure to the internet. The automatic identification by means of RFID technology is a possible expression of the Internet of Things; through sensor and actuator technology the functionality can be extended by detection of status and execution of actions.” [279]

[274] Cf. Geisberger, E.; Broy, M. (2012), p. 27
[275] Geisberger, E.; Broy, M. (2015), p. 63
[276] Cf. Bauernhansl, T. (2014), p. 16f.
[277] Cf. Hernandez, P.; Reiff-Marganiec, S. (2014), p. 1
[278] Cf. Windelband et al. (2010), p. 26
[279] Cf. Kagermann et al. (2013), p. 85

Whereas the IoS is described as follows:

"[…] part of the internet, which provides services and functionalities as granular, web-based software components. Provider make them available on the internet and offer them based on actual demand […]. Companies can orchestrate individual software components to complex but still flexible solutions (based on service-oriented architectures) […]." [280]

The offered services on the IoS fulfill a dual purpose: Both the end consumer as well as technical systems can request business functions, which are provided by partner companies. Next to the negotiability the random combinability, or rather reusability plays a major role within the IoS.[281]

The transition from the current "human-oriented" internet to the "things-oriented" internet is already in place, and the separation line between the real world and virtual one is bound to weaken.[282] The IoTS is considered the enabling element, which will integrate and interconnect different industrial sectors (see figure 7). The possibility to make random things identifiable and localizable (e.g. consumables, clothes, work pieces, tickets, household appliances, machines, transport means, plants, animals, people, etcetera) regardless of the locations of the interconnected things, opens entirely new business opportunities.[283] The entire potential and long-term results of the IoTS are not completely predictable, as it happened to the Internet in the 1960s. However, even in the short-term, forecasts say that the number of personal smart devices will be seven units pro capita and the linked industries are from multiple sources estimated around $1.9 trillion dollars in 2020. Consequently, a wide range of researchers from industry and academia, as well as businesses and government agencies are proving to be interested in the IoTS.[284] The multinational IT company CISCO Systems Inc. calls this phenomenon Internet of Everything (IoE). In their IoE Value Index Survey from 2013, the authors identified that the IoE is poised to generate at least $ 613 billion in global corporate profits in the calendar year 2013. These profits result from corporations around the globe leveraging the IoE to make their operations more efficient and provide new and/or improved customer experiences.[285]

[280] Cf. Kagermann et al. (2013), p. 85
[281] Cf. Glotzbach, U. (2009), p. 17
[282] Cf. Fortino et al. (2014), p. 2
[283] Cf. Botthof, A.; Bovenschulte, M. (2011), p. 3
[284] Cf. Fortino et al. (2014), p. 2
[285] Cf. Bradley et al. (2013), p. 1

4.3 Intelligent Objects as practical reflection of CPS in production logistics

In the section, Intelligent Objects in production logistics are going to be explained as they are considered the practical reflection of the abstract technological concept CPS within the IoTS and, thus, are seen as key technology for Industry 4.0.

4.3.1 Intelligent Object[286]

Considering the fact that CPS is an abstract, theoretical, and yet intangible technological concept, which based on the opinion of Industry 4.0 forerunner can be developed and implemented in diverse designs, the evolution of Intelligent Objects is perceived to have already a bigger practical relevance. As a key to future Industry 4.0 scenarios, Intelligent Objects have a high potential for the realization of end-to-end digital integration and subsequently for a paradigm shift in manufacturing. [287]

In literature as well as during this research process very frequently the terms CPS, Intelligent Objects, Smart Objects, Smart Products, Ubiquitous Objects, and further wording alternatives are mixed up due to indistinct definitions and characteristics. Additionally, some authors propose their original definitions and terms that seem to refer to the same or a very similar meaning. [288] Concerning the previously explained understanding of a CPS, it is certain that Intelligent Objects constitute a concrete expression of CPS. [289] The latest version of the Industry 4.0 implementation recommendation, elaborated by Acatech, refers to an Industry 4.0 component, which is a "specialization of a Cyber-Physical-System."[290] The term component is general. It determines an object of the physical or the virtual world, which adopts a certain position within a system.[291] This fact strongly correlates with the statements of Herzog and Schildhauer (2009) on the term object. While citing Alfred North Whitehead, the authors claim that an object sharply has to be differentiated from an event (process) concerning possible intelligence. Objects, in their opinion, are "entities recognized as appertaining to events", which stay the same among "the flow of events." Whereas events "happen" or "occur" and always are transformed into other events.[292] This perception of Intelligent Objects, in particular, is underlined by the theory of embodiment and, thus, confirms the objectives of this research procedure. The theory of embodiment has its origin in cognitive science, where Rodney Brooks developed it in the field of artificial intelligence

[286] Within this thesis used as proper noun and thus the initial letters are written in capitals.
[287] Cf. Meyer et al. (2009), p. 12
[288] Cf. Hernandez, P.; Reiff-Marganiec, S. (2014), p. 2 and cf. Lucke, D. M. (2014), p. 59f. In this thesis the term "intelligent" will be used as synonym with the term "smart".
[289] Cf. Capgemini Consulting GmbH (2014), p. 6
[290] Cf. Dorst, W.; Scheibe, A. (2015), p. 55 note: „Industry 4.0 - Komponente"
[291] Ibid., p. 60f.
[292] Cf. Herzog, O.; Schildhauer, T. (2009), p. 15

around 1980. The central message of the theory is that the independent evolution of intelligence necessarily requires the existence of a body (object), which can interact with its environment and, consequently, generate knowledge by experiences. Intelligence, therefore, is an expression of sensormotoric coordination, which means that sensors (sensory organs) and actuators (motors, muscles) are coordinated by intern information processing procedures.[293] Often the intelligence of an object is solely identified according to its ability of purely processing data and information.[294]

The behavior of Intelligent Objects is highly dependent on where and how they are used. An Intelligent Object deployed to monitor temperature in a freighter container behaves differently than an Intelligent Object that monitors parking spaces. [295] An Intelligent Object can obtain several characteristics. Experts currently try to estimate concrete applications of Intelligent Objects by the evolution of scenarios. Still at this time, the ideas on the use of Intelligent Objects, which vary from an instant meal, proposals on recipes projected on refrigerators and even intelligent underwear, are tough to be defined at this moment.[296] Various authors in literature claim that the status quo of already implemented Intelligent Objects is just the beginning, which scratches the surface of the full potential of Intelligent Objects (see estimation of CISCO in the previous chapter).[297] From the user perspective, the implementation of Intelligent Objects seems to be a standardized solution, as only users see the functions the Intelligent Object fulfills and the benefits it generates. This misconception is due to the lack of technical knowledge. From technical and developing perspectives, the realization of the intelligence of an object can have diverse, concrete designs.[298] For the realization of Intelligent Objects, there are various technologies available. These technologies often are called “enabling technologies” as they are perceived as a technological enabler for the innovative application of Intelligent Objects.[299] In this thesis, these technologies are called basic technologies according to the classification model on technology types, which was presented in chapter 2.1.3. Once again, it has to be pointed out in that context, that there is not one single technology behind the concept Industry 4.0, it is more an interplay of several basic technologies, which will be described in the following chapter according to their functions.

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[293] Cf. Jeschke, S. (2014), p.16
[294] Ibid. und cf. Windt, K. (2006), p. 282 note: Windt quotes Eraßme (2002), who refers to the theory of symbolism as classical model within informatics to explain „intelligence“.
[295] Cf. Vasseur, J.-P.; Dunkels, A. (2010), p. 3
[296] Cf. Mattern; Friedemann (2003), p. 21
[297] Cf. Vasseur, J.-P.; Dunkels, A. (2010), p. xix
[298] Cf. Schlick et al. (2014), p. 60f.
[299] Cf. Bildstein, A.; Seidelmann, J. (2014), p. 581

The elaborations of this chapter lead to the two following conclusion on Intelligent Objects, which were the starting point of the research initiative on technologies:

(1) Intelligence requires the existence of a body (object)
(2) Intelligence has various, different characteristics, which depend on the choice of used basic technologies

4.3.2 Intelligent Object vs. Intelligent System

Intelligent Objects can interact with the physical world by performing forms of computation as well as communicate with the outside world and with other Intelligent Objects. The true innovative power of Intelligent Objects comes from their interconnection.[300] These interconnected networks of technological systems are called Intelligent Systems. Intelligent Systems have their origin in cybernetics. Cybernetics is the most prominent representative of systems theory and explores the fundamental concepts of control and regulation of complex, hybrid systems.[301] It examines the structures, relations, and behavior of dynamic systems.[302] The innovative idea of cybernetics was to refuse to set any requirements on the type of systems (people, machines, organization, etc.), which ought to be controlled. Cybernetics was the first approach to transfer the knowledge from classical control and regulation technology to heterogeneous (technical) systems.[303] Hence, a system of "Intelligent Objects integrates Intelligent Objects and […] demonstrates through the interaction of these Intelligent Objects a kind of intelligent behavior."[304] These systems of Intelligent Objects can process data and information. This ability can be either implemented centralized or decentralized within the Intelligent Objects itself. It also can be installed in a centralized structure such as a central computer. Based on this definition, the term Intelligent Object is misleading, as the (artificial) intelligence is only created through the interaction of the members of a system – the Intelligent Objects.[305] A geographic distribution of Intelligent Objects enables totally new functionalities within the interconnected systems – this phenomenon is called emergence and is perceived to be one of the major characteristics of cybernetics (see chapter 4.5.1 for detailed description on artificial intelligence).[306]

[300] Cf. Vasseur, J.-P.; Dunkels, A. (2010), p. xix
[301] Cf. Jeschke, S. (2014), p. 7
[302] Cf. Spur, G. (1998), p. 22
[303] Cf. Jeschke, S. (2014), p. 7
[304] Cf. Deindl, M. (2013), p. 75
[305] Ibid.
[306] Cf. Gausemeier et al. (2013), p. 7 and cf. Cf. Jeschke, S. (2014), p.10

4.3.3 Conclusion

Concerning the previous explanations on Intelligent Objects and Intelligent Systems, in this thesis, the term Intelligent Object will be used instead of the construct Intelligent System with respect to the theory of embodiment and the implicit assumption, that Intelligent Objects always are integrated into an Intelligent System. In contrary to the statements on Intelligent Systems that artificial intelligence only can emerge through the interconnection of Intelligent Objects, it is concluded that a single Intelligent Object can also demonstrate a particular intelligent behavior. An object that can actively communicate its identification or position to a system is to a certain degree intelligent. Whereas the interconnection of Intelligent Objects within a system, which enables a kind of autonomous self-control and self-organization might demonstrate a higher degree of intelligence.

As Intelligent Objects are considered the key technology within the concept Industry 4.0, it is crucial to examine the following question:

- Which functions make Intelligent Objects intelligent by means of which basic technologies?

Having derived the functions and the corresponding technologies of Intelligent Objects by an extensive literature review on the characteristics of these objects, the empirical study will give valid information about their influence on end-to-end digital integration, practical relevance, and market readiness. Consequently, the functions can be applied to technology paradigm in production logistics according to its user-oriented demands.

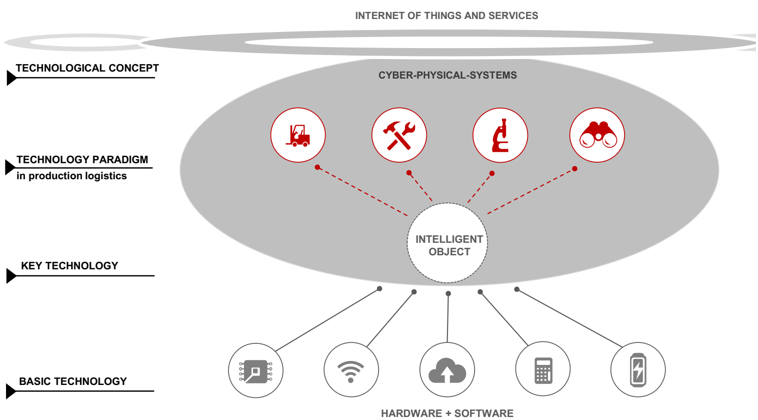

Figure 13: Hierarchical structure of technologies within the concept Industry 4.0 (Source: Own representation based on elaborations)

4.4 Hardware-based technologies and functions of Intelligent Objects

Basic technologies enable the functions of Intelligent Objects. These technologies are going to be presented in this chapter with special regards to their enabling mechanisms - their functions. The selection of technologies makes no claims to completeness; instead, it is the result of an extensive literature review on the functions of Intelligent Objects in production logistics.

4.4.1 Automatic identification and localization

Among all elaborations on the functions of Intelligent Objects, a unique identifiability is perceived as a core functionality, which constitutes the most fundamental nature of an Intelligent Object – “sine qua non” an object cannot be considered as intelligent.[307] According to DIN standard 6763, “identification” includes a “[…] unique and unmistakable recognition of an object based on essential characteristics (identification characteristics) with a predefined accuracy with regards to the targeted purpose.”[308] An automatic identification, in fact, is the connective link between the flow of material and the flow of information - the moment, where the physical and virtual world is “meld” together.[309] There are several concepts concerning the technological configuration of the identification procedure, which based on the particular requirements of an application, can be designed correspondingly. Nowadays in manufacturing industry, automatic identification using automatic identification technologies (Auto-ID) has prevailed.[310] Deindl (2013), in his framework on Intelligent Objects, defines three major dimensions of Auto-ID technologies, which include optical identification, radio identification, and network identification.[311] The optical identification mostly includes the use of barcode systems. Those systems are the worldwide standard for automatic identification and, therefore, perceived as the most important Auto-ID technology. The barcode of an item can be printed either as 1D-code (e.g. strokes) or 2D-code (e.g. matrix) and is recognized through a laser beam (scan) manually by courtesy of a barcode scanner.[312] Each sector has its barcode standards. The two most famous standards are the “Universal Product Code (UPC)” and the “European Article Number (EAN)”.[313] The disadvantages of barcode systems are a slow information flow since bar codes are a line-of-sight technology that requires manual scanning and only allows one item to be read at a time.[314] The new arousing Radio Frequency Identification technology (RFID) overcomes

307 Cf. Hernandez, P.; Reiff-Marganiec, S. (2014), p. 4
308 Cf. Arnold et al. (2008), p. 815f.
309 Ibid., p. 816
310 Cf. Herzog, O.; Schildhauer, T. (2009), p. 78
311 Cf. Deindl, M. (2013), p. 78
312 Cf. Schoch, T.; Strasser, M. (2003), p. 4
313 Cf. Schuh, G.; Stich, V. (2013), p. 273
314 Cf. Meyer et al. (2009), p. 6

these limitations. RFID is considered as the decisive requirement for the realization of the IoTS.[315] In essence, RFID technology works contactless and consists of small transponders (also called tags), which are attached to an object (e.g. item, pallet, container etc.) as well as of reading and writing devices, which communicate wirelessly with the transponder. The transponder has a mobile data storage on a memory chip and an aerial.[316] Those transponders can nearly be applied to each tangible object as their volume can be compressed to the size of a tiny black spot on a fingertip.[317] Based on estimations of the MIT (Massachusetts Institute of Technology), the costs of such a chip will decrease within the next years to 0.05 EUR/pc.[318] For the widespread use of RFID, standardization in terms of storage architecture and data exchange has to be facilitated. With the introduction of the Electronic Product Code (EPC) and the EPCglobal Tag Data Standard, the efforts for an international standard made enormous progress within the last years.[319] Through technological advance within the field of radio identification, the classical functionality of RFID can be extended with regards to an increase of decentralized intelligence, as currently most of the crucial information is centrally saved in one database. Next to the transmission of a unique identification number, other information might additionally be saved and exchanged with other systems. In production logistics, this data-on-chip principle allows to save data on, for example, transport destination, content and geometrical form of a load carrier.[320] It, furthermore, allows equipping physical objects with a digital product memory, which can be used to either ensure a complete traceability of objects or optimize manufacturing processes, while providing information on historical production data and further production steps (e.g. request bill of materials (BOM)).[321] A further application of RFID is the determination of a physical objects' position within a factory, so to speak the localization. Transport systems, e.g. AGVs, can be equipped with reading devices to read embedded RFID transponders on the floor of the factory. Hence, AGVs could be traced within a predetermined radius of movement at any time. To continue this thought strictly, materials that are transported by an AGV could also be localized at any time, as they are in the range of the AGVs' readers (given the fact that the material also has RFID transponders).[322] The localization of Intelligent Objects can be also executed by indoor GPS (Global Positioning System).[323] Indoor GPS' have the same functionality as

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[315] Cf. Botthof, A.; Bovenschulte, M. (2011), p. 3
[316] Cf. Herzog, O.; Schildhauer, T. (2009), p. 78
[317] Cf. Glotzbach, U. (2009), p. 14
[318] Cf. Schoch, T.; Strasser, M. (2003), p. 4f.
[319] Cf. Günthner et al. (2008), p. 16
[320] Cf. Günthner et al. (2008), p. 16
[321] Cf. Botthof, A.; Bovenschulte, M. (2011), p. 3f.
[322] Cf. Günthner et al. (2008), p. 16f.
[323] Cf. Kaufmann, T.; Forstner, L. (2014), p. 363

common GPS', which are used in nearly every application that is deployed outside (e.g. smartphone). In their approach, Diggellen and Abraham already presented an indoor GPS in 2001, which is based on real-time convolution of GPS signals over the entire range of possible code delays. This system has been tested in several environments and can be seen as a practical solution to the localization function.[324] As tracking and tracing functions are considered to have especially in logistics a broad field of applications, the localization function of Intelligent Objects, therefore, has a meaningful importance.[325]

4.4.2 Machine-to-machine communication

The ability of Intelligent Objects to communicate, in literature and in practice, is next to the explained functions in the previous chapter considered an integral technology of the IoTS.[326] Dorst and Scheibe (2015) describe, within their elaborations on an implementation strategy for Industry 4.0 components, the reference architecture model RAMI4.0, which explicitly deals with this issue. It implies that an Industry 4.0 component has at least to be able to communicate passively (CP2Y communication)[327] within a network. Passive communication in this context means that another superior IT system takes over the communication in form of a "deputy". The Industry 4.0 component, in this case solely, would own a unique identifier (see previous chapter).[328] A more advanced capability of communication is the so-called active (CP3Y) and Industry 4.0 conform (CP4Y) communication of Intelligent Objects.[329] This form is the common understanding of machine-to-machine communication (M2M) among Intelligent Objects experts.

The recent developments of modern high-performance communication technologies are mostly driven by progress within the private communication sector. The industrial communication uses the benefits of communications technology, which were already proven in the consumer market. The industrial Ethernet, for example, which widely is used in manufacturing environments, is based on innovations in internet communication. Hence, the classical automation technology within the fourth industrial revolution will be heavily influenced by communications technology that is currently leading the private consumer market, e.g. Wireless LAN (WLAN).[330] Communication interfaces can be differentiated by their operating range and physical installation, which includes either a

[324] Cf. van Diggelen, F.; Abraham, C. (2001), p. 6ff.
[325] Cf. Deindl, M. (2013), p. 99f.
[326] Cf. Capgemini Consulting GmbH (2014), p. 20f.
[327] Cf. VDI/VDE (2014), p. 7
[328] Cf. Dorst, W.; Scheibe, A. (2015), p. 52f.
[329] Cf. VDI/VDE (2014), p. 7
[330] Cf. Elger, J.; Haußner, C. (2010), p. 26

wired or wireless communication. [331] Table 1 presents the different types of communication technologies within the industrial environment.

Table 1: Industrial communication technologies

Area	Description	Examples
Body Area Networks (BAN)	Wireless networks with a range of approx. one meter	Near-field communication (NFC), EnOcean, Ant+ or Bluetooth Low Energy, Bluetooth 4.0
Personal Area Networks (PAN)	Wireless networks for mobile devices with a range of approx. 10 meter	(Industrial) WLAN, Bluetooth or ZigBee
Local Area Networks (LAN)	Wired or wireless networks with a range of approx. 300 meter	Ethernet, Industrial Ethernet or special field bus systems Wired field bus systems standards: Ethernet/IP, Profibus, Profinet, SERCOS, CAN-Open or M-Bus Wireless field bus systems standards: See PAN
Wide Area Networks (WAN)	Data transfer between distances of several hundred kilometers	Telecommunication standards like GPRS, UMTS and LTE

(Source: Own representation based on Lucke et al. (2014))

Concerning a complete end-to-end digital integration within the Smart Factory, M2M does not only mean communication between different field devices on the shop floor (as the name suggests) but also among various IT systems on various levels within a company.[332] For this, a unique communication standard has to be implemented, which is currently a major challenge due to the variety of manufacturer-specific standards. The communication protocol OPC-UA (OPC Unified Architecture), jointly created by 470 manufacturers of the OPC Foundation in the last years, developed to an accepted protocol family within the field of CPS technology. OPC-UA can be implemented to ensure horizontal as well as vertical communication within a factory, as long as there are no real-time critical requirements. For these so-called hart real-time requirements, classical field bus systems based on Ethernet solutions are more suitable and reliable. Thus, the OPC-UA protocol family can be used in combination with modern field bus systems as an essential connective link between MES and manufacturing level.[333] A great benefit of this kind of protocol family is its scalability and interoperability. In the automation industry, OPC-UA can be used for data and information exchange

[331] Cf. Lucke et al. (2014), p. 21f.
[332] Cf. M2M Alliance (2014), p. 4
[333] Cf. Hoppe, G. (2014), p. 264f. and cf. Plattform Industry 4.0 (2014), p. 16

independent of manufacturer, operating system, hierarchy, and topology. As a result, OPC-UA can be applied at all levels of the previously presented automation pyramid, from the smallest, energy efficient sensor over embedded field devices, PLC and gateways to operating panels, remote-control solutions within the production, mobile devices and tablets as well as on MES and ERP level.[334] OPC-UA has the potential to establish itself as de-facto standard for data and information exchange for non-real time critical applications within the concept Industry 4.0, as it is perceived to be impossible to define an entirely new communication standard.[335] Concerning the transportation protocol of M2M communication, Vasseur and Dunkels (2010) were discussing in detail the benefits of the use of TCP/IP protocol architecture (Transmission Control Protocol/ Internet Protocol) in comparison to traditional gateways. An IP-based architecture of Intelligent Objects is interoperable across devices and communication technologies, evolving, and versatile while stable, scalable, and manageable, and simple enough that a resource-constrained Intelligent Object can easily run it while gateways have an inherent complexity and lack of flexibility and scalability.[336]

4.4.3 Energy supply

Intelligent Objects fulfill various functions by courtesy of their technological means. These objects require energy to carry out processes and tasks they are intended for. Intelligent Objects gather demanded energy either from external sources or by generating it autonomously. Usually, the complexity of tasks is proportional to energy consumption. Therefore, the more energy the objects obtain, the more complex the functions they execute become.[337]

The mobile electricity supply for Intelligent Objects still is a big challenge nowadays. Despite the significant efforts to increase the energy density of batteries, current successes cannot keep up with the rising energy consumption of modern processors. The energy density of batteries in average increases in 10 years by the factor of four, whereas the performance of processors doubles nearly every two years (see Moore's Law in chapter 4.1). Thus, the energy supply for mobile Intelligent Objects is a restraining factor for the practical use of Intelligent Objects.[338] There are mainly four different possibilities to supply energy for Intelligent Objects: no energy supply[339], wired energy

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[334] Ibid, p. 327
[335] Ibid, p. 341
[336] Cf. Vasseur, J.-P.; Dunkels, A. (2010), p. 29ff. and cf. Sánchez López et al. (2012), p. 297
[337] Cf. Hernandez, P.; Reiff-Marganiec, S. (2014), p. 4
[338] Cf. Herzog, O.; Schildhauer, T. (2009), p. 88
[339] It is questionable, if an Intelligent Object is able to fulfill „intelligent" functions without any energy supply. Thus this option will not be presented in detail.

supply, inductive energy supply, and internal energy supply.[340] Wired energy supply can only be applied to stationary, place bounded Intelligent Objects, e.g. production machines, as the Objects have a wired connection to the power grid.[341] A good example for inductive energy supply is passive RFID systems (see chapter 4.4.1). The necessary energy for operating the RFID chip and communication is transmitted by the reading or writing device. Active transponders have a battery and, thus, can supply themselves with energy.[342] The latter is the first form of an internal energy supply, which is a dependent energy supply. This kind of energy supply is realized according to the current state of the art by use of a battery or a lithium-ion accumulator, which has to be recharged at periodic intervals and, thus, makes this form disadvantageous. Therefore, it is persuaded to make Intelligent Objects energy self-sufficient. Energy self-sufficient Intelligent Objects generate the required energy from its environment without using any additional energy source.[343] This technology is called energy harvesting. There are several approaches to use natural energy from the environment based on, for example, thermoelectric sources, piezoelectric generators, or solar energy sources (photovoltaic).[344] The most famous form that already has several applications in productive systems is the solar energy harvesting, which, for example, is used in logistics to track containers.[345] As solar energy in most cases only makes sense outside factory buildings, thermoelectric harvesting is perceived to have enormous potential in manufacturing environments. A thermogenerator module is employed to harvest energy from temperature gradients between a heat source, e.g. persons and animals, machines, or other natural sources.[346]

4.4.4 Sensing and actuating

A living being can only exist, if it can react to environmental influences. Every living being is naturally equipped with biological structures to pick up external stimuli that are described as receptors. Nerves transform external stimuli into electrical signals and then are further transferred to the central nervous systems (brain), where a sensory impression (perception, feeling) arises.[347] Sensors are, in particular, the technical reproduction of these natural processes. One function of Intelligent Objects is the collection of data from its environment using sensors. Subsequently, the physical world can be faithfully recreated in real-time, by which an accurate control of physical

[340] Cf. Deindl, M. (2013), p. 117f.
[341] Ibid.
[342] Cf. Herzog, O.; Schildhauer, T. (2009), p. 78f.
[343] Cf. Windelband et al. (2010), p. 29
[344] Cf. Mateu et al. (2005), p. 5ff.
[345] Cf. Windelband et al. (2010), p. 29
[346] Cf. Mateu et al. (2015), p. 1
[347] Cf. Hesse, S.; Schnell, G. (2011), p. 1

processes can be guaranteed. A fusion of digital and material world is the result.[348] Sensors and related measuring systems provide the essential, directly measurable information for mechatronic systems. Thus, they are important connective links between processes and information processing parts of microelectronics. In this context, the most relevant sensors are the ones, which collect mechanical or thermal measures and create an electric measuring signal. Technical sensors can be classified according to its measured variable. Most important variables are mechanical, thermal, electrical and chemical and physical variables. Table 2 shows a few examples based on the before mentioned classification, to allow the reader obtaining a better understanding of the opportunities of sensors.[349]

Table 2: Sensing classification according to measuring variables

Classification		Measuring variable
Mechanical variables	e.g. Kinematic variables	Velocity, rotation speed, acceleration, vibration, flow rate
Thermal variables	e.g. Temperature	Contact temperature, radiation temperature
Electric variables	e.g. Electric state variables	Voltage, current, electrical power
Chemical and physical variables	e.g. Optical variables	Intensity, wave-length, colour

(Source: Own representation based on Isermann (2008))

Concerning sensing technologies, classical sensors serve as a first element of a whole measuring chain. This chain includes fundamental measuring processes such as the collection of measuring variables, preprocessing of signals, processing of signals, signal amplification, and analog-digital conversion.[350] Classical sensors simply collect measuring variables and transform them into an electrical signal. Whereas newer generations of semiconductor-based sensors, the so-called smart sensors, have the ability to transform collected signals into digital data and, further, process it into valuable information. In other words, they can cover the whole measuring chain.[351] Smart sensors can also dispose a communication interface to interact with other smart sensors. In combination with an embedded microprocessor, these systems are called MEMS (Micro

[348] Cf. Lucke et al. (2014), p. 15
[349] Cf. Isermann, R. (2008), p. 413ff.
[350] Cf. Cf. Isermann, R. (2008), p. 415
[351] Cf. Hesse, S.; Schnell, G. (2011), p. 7

Electromechanical Systems) and are considered an own CPS.[352] This technological progress of sensing technologies evolves a new form of data collection, namely using wireless sensor networks. By use of a communication device, the aforementioned smart sensors can exchange processed data among themselves.[353] The concept of wireless sensor networks is similar to that of Intelligent Objects, and much of the development in Intelligent Objects has occurred in communities dealing with wireless sensor networks. Wireless sensor networks are composed of small nodes that autonomously configure themselves into networks through which sensor readings can be transported.[354] By using sensor networks, it will be able to make accurate observations on real world sceanrios in various sectors, as it has never been possible before.[355] In plant automation, the interconnection of sensors and actuators by courtesy of field bus systems has even developed state of the art. Important criteria for the implementation of wireless sensor networks are speed, real-time capability, transmission reliability, and a low price level for the connection. Proven field bus systems are, AS-I, Interbus, and Profibus DP.[356] Wireless sensor networks open entirely new opportunities for the collection of context-specific information of Intelligent Objects. Context is defined as the quantity of information that is needed for the characterization of a situation, people, and objects, that is relevant for the interaction between a user and an IT application. Context-sensitive systems enable an application-specific use of context information as well as the adaption of behavior to the identified situation.[357] Context sensitivity is the topmost objective of current research and development activities.[358] Technological developments that can contribute to a practical solution are sensor fusion, meaning fusion of data from several different sensors, which are based on the above-explained sensor networks as well as pattern recognition, which is a characteristic of the optical measuring variable within the sensing classification scheme (see Table 2).[359] Wireless sensor networks have limitations due to the physical size of sensor nodes. The vision of smart dust, which was developed around 2000, pursuing the idea of small dust specks that could be dispersed using mechanisms such as air flow. Their usage in military to track the location of enemies was cancelled due to the restrictive nature of physical sensor size.[360]

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[352] Cf. Lucke et al. (2014), p. 11f.
[353] Cf. Schoch, T.; Strasser, M. (2003), p. 6
[354] Cf. Vasseur, J.-P.; Dunkels, A. (2010), p. 12
[355] Cf. Mattern; Friedemann (2003), p. 18
[356] Cf. Hesse, S.; Schnell, G. (2011), p. 378
[357] Cf. Gorecky et al. (2014), p. 532
[358] Cf. Glotzbach, U. (2009), p. 23
[359] Cf. Geisberger, E.; Broy, M. (2015), p. 129f.
[360] Cf. Vasseur, J.-P.; Dunkels, A. (2010), p. 12

Actuators, on the other hand, influence technical processes using a final control element, which can change certain process parameters - they are able to technically manipulate the physical world.[361] It is an essential part, comparable to sensors, within a mechatronic system. The functioning of an actuator goes beyond the often-assumed pure drive. A whole system of programs, electronics, and mechanics that transforms electrical signals from an information-processing unit into movements, forces, and resulting torques.[362] The type of actuator strongly depends on the purpose of its implementation. The mode of action of actuating systems is the same. The actuator receives an electrical signal (information) of a control unit and transfers it to an energy-adjusting element. This exchange can be, for example, a relay or a switching valve. The energy for the manipulation of physical processes is provided by the auxiliary energy element. Auxiliary energy can be transmitted in different forms; most common are thermal energy sources (e.g. thermal expansion), chemical energy sources (explosion pressure), fluid-based energy sources (e.g. pneumatic, hydraulic), and electrical energy sources (e.g. magnetic fields). Auxiliary energy is doing the actual work of an actuator. Hence, it is also called actuating or adjustment energy. [363]

4.4.5 Data and information processing

The previous chapters' foremost explained data generating and exchanging functions and technologies. To make efficient use of the collected data, additional technological components are required to process data. [364] In literature, several authors define the intelligence of Intelligent Objects solely according to the degree of their capability to process data and information. Even though this approach seems to be a bit too narrow and furthermore contractionary to the theory of embodiment (see chapter 4.3.1), the processing function is essential for all further considerations on decentralized and autonomous behavior of Intelligent Objects. The function of data and information processing can be implemented, based on the location of the processing procedure, in three ways: Outside an Intelligent Object, embedded within an Intelligent Object, and in a combined way of both previous mentioned alternatives. The processing of data and information outside an Intelligent Object requires real-time capable communication interfaces embedded in a physical object. Sensors collect data and transfer it to a central IT system, where the actual processing procedure takes places. In some applications, data from various sources can be aggregated, transformed into information, and transferred back to an Intelligent Object. Decentralized data and information processing

[361] Cf. Isermann, R. (2008), p. 441
[362] Cf. Lucke et al. (2014), p. 19
[363] Cf. Isermann, R. (2008), p. 442ff.
[364] Cf. Windelband et al. (2010), p. 28 f.

requires directly embedded processing qualities on the Intelligent Object.[365] The objective of data and information processing, independently of the location of the processing procedure, is to prepare information in such a manner that decision-making processes are optimally supported. To which degree information is processed strongly depends on the application itself (e.g. who is allowed to make a decision based on the information e.g. Intelligent Object, employee, etc.).[366] The technological implementation of local data and information processing is realized by microprocessors or rather microcontroller. A microcontroller is a microprocessor with built-in memory, timers, and hardware for connecting external devices such as sensors, actuators, and communication devices. Microcontrollers have two types of memory: Read-Only Memory (ROM), and Random Access Memory (RAM). ROM is used to store the program code that encodes the behavior of the device and RAM is used for temporary data the software needs to do its task. The purpose of a microcontroller is to run its software programs. The software is stored in the ROM and is typically already on the microcontroller when the device is manufactured. The software is mainly programmed in high-level languages, such as C, Pascal, or Forth.[367] These small computers are also known as embedded systems, if they are embedded in something other than a computer (e.g. PC, laptops, and other equipment readily identified as a computer). The primary difference between a traditional embedded system and Intelligent Objects, which suits the thesis' comprehension, is that communication is typically not considered a central function for embedded systems, whereas communication is an elementary characteristic for Intelligent Objects (see chapter 4.4.2).[368] Embedded systems, therefore, can be seen as early manifestations of Intelligent Objects.[369]

4.4.6 Human-machine interaction

Despite the increasing number of Intelligent Objects within future factories, numerous decisions will still be made by people. Thus, the interaction of Intelligent Objects has to go beyond the communication with other Intelligent Objects and IT systems (M2M communication, see chapter 4.4.2). Intelligent Objects interact with its users via Human-Machine-Interfaces (HMI). Input devices transfer user's actions in digital language, whereas output devices are used to represent computing language in a comprehensible way for the user.[370] HMI are integrative parts of hardware and software components, which make information and control elements available to support the user to fulfill

[365] Cf. Deindl, M. (2013), p. 83
[366] Cf. Schuh et al. (2014), p. 286
[367] Cf. Isermann, R. (2008), p. 536f.
[368] Cf. Vasseur, J.-P.; Dunkels, A. (2010), p. 7
[369] Cf. Herzog, O.; Schildhauer, T. (2009), p. 81
[370] Ibid., p. 92f.

his/her tasks.[371] For HMI nowadays, there are many technologies on the market. Some of them have already proven their practical relevance in everyday use. Considering the input devices, voice control, for example, is seen beneficial, as the users visual and haptic capabilities are not interfered, while interacting with the Intelligent Object. Apple's "personal assistant" Siri is a good example of a voice command HMI.[372] Another revolutionary technology is the control by gestures. It is considered intuitive and immediate, and is already available for simple applications (e.g. Microsoft's Kinect).[373] The recognition of the hand's movements can be executed either image-based (e.g. camera-based procedures of object detection) or device-based (e.g. On-Body sensor networks or data gloves).[374] Classical touchscreens are perceived to be the most important form of HMI input devices in future. New technologies such as Dispersive Signal Technology enable the usage of a touchscreen even in abrasive, industrial environments. These so-called ruggedized hardware solutions bring along industry-suited characteristics (e.g. dust protection, weatherproof protection, etc.).[375] The technologies especially have an additional value in manufacturing, when they are used as personalized assistance systems, providing users context-sensitive information (see chapter 4.4.4). Within these systems, not only information will be supplied but also recommendations on decision-making based on previously aggregated data. A characteristic feature of an advanced HMI output device is a comprehensible visualization of the information.[376] Currently, normal displays are used as output device. To achieve greater efficiency, it will be necessary for Intelligent Objects to recognize users' intentions and plans (e.g. feelings) and anticipate human behavior. Hence, Intelligent Objects would show human awareness. Technologies such as user and human modeling enable the diagnosis, simulation, prediction, and support of human behavior in interactions with Intelligent Objects. Current research is focused on two applications: the "virtual test driver" and the "empathic virtual passenger". Other technological approaches include rule-based production systems, Bayesian networks, mathematical control theory, Markov decision processes, and various combinations of these methods.[377] Atzori et al. (2014), in analogy to the human evolution, talk of a similar evolutionary path from *smart objects* (res sapien) over *acting objects* (res agens) to what they call *social objects* (res socialis). A social object would have a social consciousness, which would be part of a social community of objects and devices - a social IoT.[378]

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[371] Cf. Lucke et al. (2014), p. 20
[372] Cf. Gorecky et al. (2014), p. 530f.
[373] Cf. Geisberger, E.; Broy, M. (2015), p. 134
[374] Cf. Gorecky et al. (2014), p. 530f.
[375] Cf. Gorecky et al. (2014), p. 530f.
[376] Cf. Schuh et al. (2014), p. 293
[377] Cf. Geisberger, E.; Broy, M. (2015), p. 134f.
[378] Cf. Atzori et al. (2014), p. 98

4.5 Software-based technologies and functions of Intelligent Objects

Having described hardware-based technologies of Intelligent Objects, now a special focus has to be set on software components, which enable additional functions of Intelligent Objects.

4.5.1 Excursus: Artificial intelligence (AI)

In the field of autonomic technologies[379], current researchers are especially focusing on the transformation of intelligence into technical systems based on ICT. The objective is to transfer parts of human behavior, esp. of decision-making processes, into technical artifacts - Intelligent Objects.[380] The term artificial intelligence (AI) describes this transmission. AI triggers emotions, as it arouses questions such as "What is intelligence," "How can intelligence be measured," and "Is there a possibility that machines will behave like human beings." Furthermore, the term artificial might also trigger fears, as people might associate science-fiction robot human, which overtake the world. Hence, a clear definition of what constitutes AI in literature is problematic to find.[381] A very pragmatic, though appropriate definition, was made by Elaine Rich in 1983. He defines AI as "[…] the study of how to make computers do things at which, at the moment, people are better." Ertel claims that Rich's definition currently is still relevant and also will be in 2050. He backs up his argument by stating that computers are far better than human beings are, for example, in the execution of calculations within short time periods. In numerous other examples, human beings are still superior to computers, especially when it gets on optimal decision-making and planning of actions based on experiences. Thus, AI tries to develop, based on research in cognition science, methods, and technologies that let machines think and act like human beings.[382] In essence, there are five capabilities for the description of AI:

- Rational acting
- Logical reasoning
- Cognitive behavior
- Emergence
- Decision-making ability

[379] No explicit translation of the German term *Autonomik* in English language.
[380] Cf. Botthof, A.; Bovenschulte, M. (2011), p. 1
[381] Cf. Ertel, W. (2013), p. 1
[382] Ibid., p. 2f.

These capabilities combined, describe human beings' ability to learn and solve problems. Consequently, a translation of this combination into a software-based program can be interpreted as AI.[383]

In conformity with the explanation on Intelligent Systems in chapter 4.3.2, a distributed AI (also called collective AI) can emerge using cooperation of spatially distributed technical systems. To achieve such an artificial intelligence within a system, the individual objects to a certain degree have to be intelligent (e.g. owe a microprocessor), too.[384] This meets the requirements for the theory of embodiment so that it can be concluded that the combination of software-related functions of AI and previously in detail described hardware-based functions of intelligence, constitute the whole range of intelligence for physical objects and systems.

4.5.2 Autonomy of action

Software agents are an useful technology to implement Intelligent Objects, as the concept of agents is close to the concept of Intelligent Objects.[385] Wong et al. (2002) define a software agent as "[…] distinct software process, which can reason independently, and can react to change, induced upon it by other agents and its environment, and is able to cooperate with other agents."[386] A spam filter, for example, is an agent, which separates desired and undesired (spam) arriving e-mails and eventually deletes them.[387] There are six characteristics, which describe a software agent:[388]

- Situated: Existence within an environment
- Reactive:[389] Adaptation of behavior to information of the environment
- Autonomous: Possession of a certain degree of an autonomy of action
- Social: Ability to cooperate with other agents (multi-agent system)
- Rational: Execution of actions to fulfill an objective
- Anthropomorphic: Representation of mental concepts of human beings

Based on these characteristics, four different types of agents can be defined, which increase in intelligence with each stage:[390]

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[383] Cf. Bogon, T. (2013), p. 12f.
[384] Ibid., p.18
[385] Cf. Meyer et al. (2009), p. 9
[386] Wong et al. (2002), p. 2
[387] Cf. Ertel, W. (2013), p. 13
[388] Cf. Roidl, M. (2010), p. 69f.
[389] Some authors claim that *pro-activeness* (exhibition of a goal-directed behavior by taking the initiative) is as well an essential characteristic (Meyer et al. (2009)).
[390] Cf. Roidl, M. (2010), p. 66ff.

- **Simple reflex agent**: Choice of action based on actual perceptions (no consideration of previous perceptions).
- **Model-based reflex agent:** Choice of action based on a model of the environment and past additional perceptions (inner state). Model-based reflex agents can react to unexpected situations based on earlier experiences (matching with the inner state).
- **Goal-based agent:** Choice of action based on actual and past perceptions, and a desirable state.
- **Value-based agent:** Choice of action based on the optimal solution to fulfill a desirable state.

Software agents, moreover, can be implemented as encapsulated solutions of its physical object (e.g. machine), which allows a simple migration of individual machines and even globally, interconnected objects. To simplify the connection of new objects, software agents can be implemented as a single entity or as an integrative part in a machine.[391] These agents enable, dependent on the usage, a decentralized and (partially) autonomous behavior of Intelligent Objects based on self-control functions. The self-control of Intelligent Objects describes the process of decentralized decision making in heterarchical structures. Thus, it requires the ability of Intelligent Objects to make autonomous decisions in non-deterministic systems according to predetermined goals. Predetermined goals are essential to the existence and success fulfillment of self-controlled process, as they set an ending point of an event or process, which has to be achieved.[392] Essential characteristics for self-control of Intelligent Objects, according to Windt (2006), are described as follows:[393]

- Autonomous, goal-oriented behavior
- Ability for autonomous decision-making
- Ability for measuring, back coupling and evaluation of events
- Ability for interaction
- Heterarchy
- Non-determinism

Schulz-Schäfer (2008) very explicitly investigates the autonomy of Intelligent Objects. He divides autonomy into three dimensions. Based on the degree of autonomy of each dimension, an increasing form of self-control is possible to realize. The dimensions are:[394]

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[391] Cf. Vogel-Heuser et al. (2014), p. 154f.
[392] Cf. Windt, K. (2006), p. 284
[393] Ibid., p.284ff.
[394] Cf. Schulz-Schaeffer, I. (2008), p. 42 f.

- **Behavior autonomy:** The ability to execute predefined behavior programs.
- **Decision-making autonomy:** The ability to choose between different behavior programs.
- **Information autonomy:** The ability to generate new behavior programs based on new information.

These three dimensions of autonomy can be brought together and considered the autonomy of action.[395] The characteristics of self-controlling Intelligent Objects can be implemented with the different, previously mentioned types of software agent programs. It strongly depends on how much autonomy of action and, subsequently, artificial intelligence is supposed to be decentralized considering the objective of an application. For an efficient use of software agents within a system, multi-agent systems (MAS) can be implemented. In multi-agent systems, software agents cooperate and negotiate with other agents.[396] The idea behind MAS comes from the animal world. The highly complex behavior of migratory birds in swarms repeatedly astonishes the observer. It seems, that the behavior previously has been "negotiated" and a plan for their trip has been developed, which each of the bird is following by its own. On external influences, the swarm reacts in a formation as a whole, coordinated unit. As varied the strategies of each bird might be, it appears that each acts to the benefit the entire group.[397] This natural phenomenon is called swarm intelligence. In MAS, the cooperation among agents is a decisive aspect, which generates new benefits based on the interaction of agents. In organization theory, coordination describes the mutual agreement of individuals among a system to serve a superior system goal.[398] Self-organization of a system is characterized by its ability to solve complex problems based on a collective procedure.[399] Agents harmonize their actions with each other so that a problem is strategically tackled and solved in a jointly coordinated manner. The problem-solving process is divided into three phases: problem decomposition, solving of sub-problems, and fusion of partial solutions.[400] In MAS, ontology is inevitable for a successful operation and efficient functionality. Ontology includes a predetermined vocabulary for the communication between agents. Without this and a subsequent semantic connection of the vocabulary, meaningful communication cannot take place.[401]

[395] Cf. Botthof, A.; Bovenschulte, M. (2011), p. 5f.
[396] Cf. Geisberger, E.; Broy, M. (2012), p. 132
[397] Cf. Broy, M. (2010), p. 33f.
[398] Cf. Deindl, M. (2013), p. 81
[399] Cf. Bogon, T. (2013), p. 18
[400] Cf. Roidl, M. (2010), p. 72f.
[401] Cf. Libert et al. (2010), p. 83

4.5.3 Advanced data analytics

According to analysts from International Data Corporation, the volume of generated data is expected to grow forty to fifty-folds between 2010 and 2020, to 40 zettabytes. To make the dimensions comparable for the reader, six terabytes of data will be stored for each of the world's inhabitants by 2020, equivalent to the amount of text contained in three million books.[402] In manufacturing, the mountain of data is also expected to increase proportionally with the use of Intelligent Objects and its components (e.g. sensor, sensor networks).[403] This phenomenon is called big data. In future, the transformation of "big data" into valuable "smart data" will be a main challenge, which in the end increases the efficiency of processes when it is used appropriately.[404] The automated recognition of relations, meanings, and patterns using advanced data analytics technologies, can generate additional benefit.[405] These software-based technologies range from data mining methods to complex machine learning programs. Data mining tools enable, for example, the generation of new application and context-specific information using data aggregation from different sources. The analyzing algorithms depend on the problem to be solved. Data mining methods have to be implemented use case specifically.[406] The multinational software company SAP SE addresses the topic by means of their In-memory platform[407], SAP HANA. It was developed to process and analyze large volumes of data in real-time. SAP HANA is already successfully in use in machine-to-machine application scenarios (M2M), where a comprehensive data analysis was previously extremely time-consuming or impossible. These include, for example, a condition-based maintenance, predictive analytics of malfunctions or the automatic replenishment of consumables based on current production status and short-term product demand forecast.[408]

The next evolutionary step, based on advanced analytic methods, is self-optimizing Intelligent Systems. Intelligent Objects of such a system are equipped with cognitive skills. Based on machine learning technologies, historical data can be used to make a decision based on experiences. Thus, Intelligent Objects would have the ability to optimize their behavior.[409] Neural networks are an essential prerequisite and simultaneously the key to successful machine learning. Neural networks learn from examples, recognize patterns, and use past measurement data to make forecasts and

[402] Cf. Heuring, W. (2015), p.1
[403] Cf. Schöning, H. (2014), p. 548
[404] Cf. Kaufmann, T.; Forstner, L. (2014), p. 365
[405] Cf. Weber, M. (2013), p. 10
[406] Cf. Pötter, T. et al. (2014), p. 168 ff.
[407] Data is saved on an "in-memory database", not as usual, on a disk storage.
[408] Cf. Kleinemeier, M. (2014), p. 573
[409] Cf. Günthner et al. (2014), p. 297

ideal models regarding the future behavior of complex systems.[410] Self-optimizing systems, as well as self-controlling and self-organizing systems, have superior system goals. In manufacturing, these goals might be a “Reduction of lead time”, “Reduction of energy consumption”, or “Increase of quality”.[411] Hence, cognitive, self-optimizing systems have abilities that go beyond the previous mentioned control and organizing activities. Self-optimizing systems can fulfill complex planning tasks for a longer period.[412]

4.5.4 Digital integration platforms

The objective of an end-to-end digital integration within a Smart Factory can be facilitated by the use of so-called smart services on digital integration platforms[413]. The integration of Intelligent Objects via IoTS enables the field data level to be accessed from any location.[414] An integration platform includes hardware, software, and communication systems.[415] Kagermann et al. (2013) define integrative CPS platforms as federated units. Federally, in this context, means that services and applications can be used by different participants together for cooperative activities.[416] Hence, in some literature, digital integration platforms are also described as individual ecosystems of virtual marketplaces.[417] On these platforms, Intelligent Objects can both offer services and make use of services depending on individual needs.[418] A special application of a digital integration platform in manufacturing is a technology data marketplace. It occurs as an intermediary between demand and supply sides of digital data (e.g. process parameters) and provides only the necessary transparency for all types of security. Intelligent Objects can use offered technology data, for example, to maintain their components.[419] Consequently, the original functionalities of Intelligent Objects can be extended by the temporary use of particular services.

Based on the requirements for the hardware of such digital integration platforms, cloud-computing approaches, which have already proven their efficiency in practice, are considered a meaningful solution.[420] Cloud computing is characterized by scalability, high availability, fast network connection and thus, the provision of functionality using defined interfaces a fundamental technology for implementing Industry 4.0 scenarios.[421]

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[410] Cf. Siemens (2015)
[411] Cf. Gausemeier et al. (2013), p. 11
[412] Cf. Günthner et al. (2008), p. 26
[413] The term is used as synoynm with the term CPS platform.
[414] Cf. Kagermann, H.; Riemensberger, F. (2015), p. 11
[415] Cf. Plattform Industry 4.0 (2014), p. 18
[416] Cf. Kagermann et al. (2013), p. 85
[417] Cf. Geisberger, E.; Broy, M. (2012), p. 183
[418] Cf. Diemer, J. (2014), p. 390f.
[419] Cf. Kagermann, H.; Riemensberger, F. (2015), p. 60 ff.
[420] Cf. Geisberger, E.; Broy, M. (2012), p. 223
[421] Cf. Fallenbeck, N.; Eckert, C. (2014), p. 404

Cloud services can be employed on different hard and software levels such as Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS), and Infrastructure-as-a-Service (IaaS) solutions.[422] In cloud systems, data from manufacturing processes runs together on a server, is analyzed, and goes back to its destination. Apple's Siri is an example of this functionality. A voice command is recorded through the microphone, the sound file is sent a server, where it is evaluated, and the result is transmitted as a control command to the sender unit.[423] These functions can be offered as services on digital platforms based on cloud systems. It is even conceivable that these services will be purchased in the form of apps. Apps are small software solutions. They have pre-defined functions for a limited remit and are comparable to the idea of services.[424]

4.6 Conclusion

The Industry 4.0 technolgies CPS and IoTS are currently theoretical technology concepts, which therefore, are intangible and hard to work with for a technology supplier and, especially, technology user. Hence, a practical reflection of these concepts is attributed to Intelligent Objects. Intelligent Objects consist of several hardware-based and software-based technological configurations. A selection of its functions and technologies have been described in the previous chapters based on an extensive literature review[425]. When used in combination, hardware-based technologies form a mechatronic system (see figure 14)[426]. This combination is building up the hardware setup of an Intelligent Object. A mechatronic system combines three different technology areas: mechanical engineering, electrical engineering, and information technology. It translates the interconnection of these technology disciplines and makes them implementable. The decision of which identified technologies are used to form an Intelligent Object is strongly dependent on its usage and its application (technology paradigm).

The software-based technologies predominantly are used to enhance the functionality of the information-processing unit of Intelligent Objects. Intelligent Objects might be implemented in production logistics with different technological components, which have been described in the previous chapters. In chapter 6, possible exemplary manifestations of Intelligent Objects in production logistics will be presented to illustrate the bandwidth of possible implementation scenarios in a logistics environment.

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[422] Cf. Bildstein, A.; Seidelmann, J. (2014), p. 587
[423] Cf. Verl, A.; Lechler, A. (2014), p. 238
[424] Cf. Bildstein, A.; Seidelmann, J. (2014), p. 587
[425] A summary of the technologies and functions can be found in appendix 1.
[426] Cf. VDI 2206 (2004), p. 14

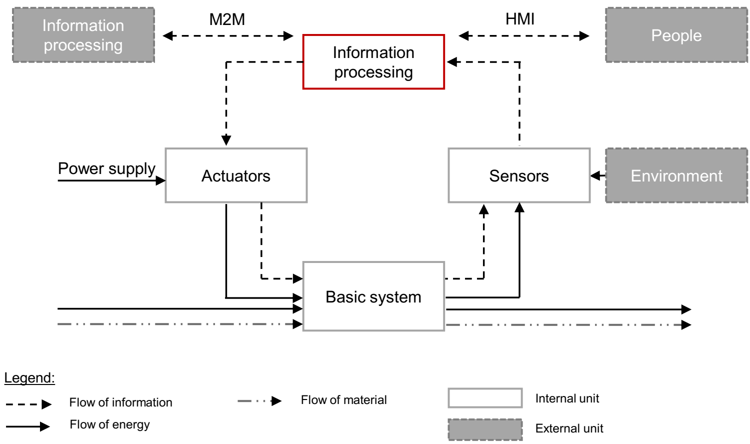

Figure 14: Basic structure of a mechatronic system
(Source: Own representation based on VDI2206 (2004))

5 Empirical study

The following chapter is devoted to the application of the scientific method to determine the influence of the identified functions and technologies on end-to-end digital integration.

5.1 Online survey as sampling technique

The present empirical study is a requirement research and can be specified by the following characteristics: Generation of strategic knowledge using an individual, statistics method based on selective data in a specific area.[427] Requirement research is the opposite of fundamental research. Atteslander defines requirement research as "[…] empirical social research, which especially aims to develop instructions, for instance, for political actions or for market decisions."[428]

To generate meaningful data, an online questionnaire[429] was developed in courtesy of the software tool, Google Drive. Within the questionnaire, an ordinal scale with different response levels was used. Depending on the question, a five-step scale ("No" to "Very high") or a three-step scale ("0-3 years" to "7-10 years") for the evaluation of the questions has been developed. From qualitative characteristics, ordinal variables could be generated. To achieve a high level of standardization of the questionnaire, entirely open questions have been avoided.[430] Furthermore, direct questions have been applied. With this, the expression of subjective opinions, as it would be the case with indirect questions, was prevented.[431] Merely, a field with "further comments" was deliberately chosen to give the participants of the survey the chance to provide additional information on the questions.

Overall, there have been 13 functions identified in the last chapter, on which the application of the ordinal scale has been applied. For each function, the three following essential elements were evaluated with the aim to derive technology potential afterwards (see chapter 2.2.2):

(1) Influence on end-to-end digital integration
(2) Practical relevance
(3) Market readiness

Hence, altogether, the participants of the questionnaire had to evaluate 39 questions.

[427] Cf. Atteslander, P. (2010), p. 58
[428] Ibid.
[429] The complete online questionnaire can be found in appendix 3.
[430] For more information on the use of open questions see Atteslander, P. (2010), p. 478
[431] Cf. Berekoven et al. (2006), p. 100ff.

C.J. Bartodziej, *The Concept Industry 4.0*, BestMasters,
DOI 10.1007/978-3-658-16502-4_5

For a common understanding of the functions and consequently a better result, a short description of the main constituting elements of the function has been given. Figure 15 shows an exemplary function to illustrate the design of the questionnaire.

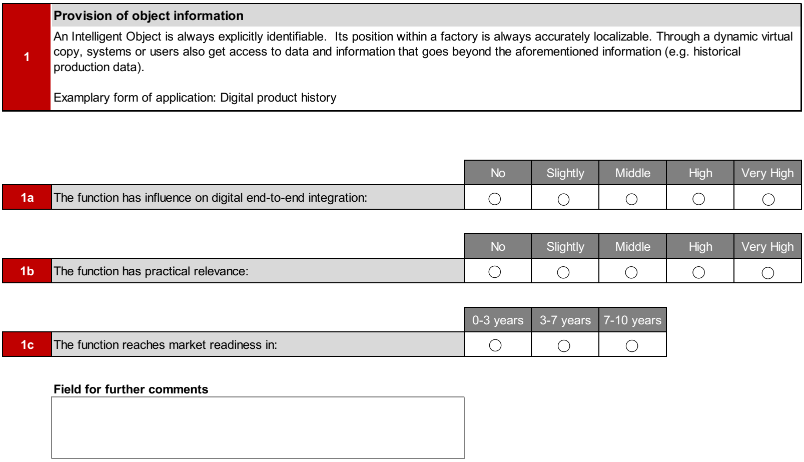

Figure 15: Exemplary illustration of questionnaire design
(Source: Own representation)

None of the respondents could distort the data by answering the same question repeatedly. The respondents had the chance to correct themselves using a "back" button. They also were able to drop out of the questionnaire before they finished it completely. Thus, the correctness and representativeness[432] of the survey was ensured. At the end of the questionnaire, the participants could express their desire to get information on the results. With the confirmation of a "submit" button at the bottom of the questioner sheet, all the data has been transferred to the server, where it was stored.

5.2 Selection of experts

Industry 4.0 experts were the primary target group of the online questionnaire. Due to the far-reaching scope, heterogeneity and complexity of the topic Industry 4.0 (see chapter 3.2.3) a particular limitation of the target group was refused. At the current state of development, it was complicated to draw a clear line between Industry 4.0 "interested person", "involved person", and "person with special expertise". Based on Ammon (2009)

[432] For more information on the term *representativeness* see Kuß, A. (2011), p. 59f.

and his description of the selection of experts for the execution of a Delphi study, an expert is a person that is acting in relevant areas to the topic and has certain experience within this field.[433] Experts have to be familiar with the subject matter and have to have already dealt with the issue of content.[434] In this context, exceptional attention was paid to Industry 4.0 experts, which, in particular, deal with topics in the wider field of innovative technologies, innovative technologies in logistics, digitalization, and automation. Hence, the primary target group included people from various professional backgrounds. The online survey was aimed at representatives from private and public institutions (e.g. research institutes), organizations, and companies in the field of Industry 4.0. The experts, on the one hand, were addressed on the professional network XING. XING is a social software platform for enabling small-world networks for professionals, which offers personal profiles, groups, discussion forums, event coordination, and other common social community features. In order to address the experts, a short introduction (description, goals, time) and link to the online questionnaire was placed in 12 XING groups[435], which are thematically related to the topic Industry 4.0. A special focus has been set on groups, were technological topics were predominant to reach the primary target group optimally. Additionally, particular group members that listed up “intelligent technologies” in their profile under the points “I offer” and “Interests”, were asked for the participation in the survey via personal message. On the other hand, experts were addressed via personal e-mail. This expert pool consists of contacts from former workplaces, university environment, and contacts based on recommendations. In addition, the experts were invited to request competent colleagues and contacts to participate in the questionnaire if their availability was limited due to time constraints.

Because of the timeliness of the topic Industry 4.0, a high interest of respondents was assumed. Beforehand to the release, a response of 30 evaluable questionnaires was expected and, thus, defined as a target. To achieve this objective, an overall sample size (n) of approx. 600 experts should have been addressed, based on an assumed response rate of 5-20% (common response rate for online questionnaires)[436]. Due to the open structure of the platform XING and its groups, an overall sample size cannot be measured, as the group members were merely asked indirectly for participation in the form of a call for participation.[437] Hence, a measurable response and dropout rate will not be provided.

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[433] Cf. Ammon, U. (2009), p. 460
[434] Cf. Häder, M.; Häder, S. (1995), p. 15
[435] For the selection of groups see appendix 2.
[436] Cf. Fankhauser, K.; Wälty, H. F. (2011), p. 67
[437] The call for participation was made two times within each group, to increase the number of respondents.

5.3 Restrictions of empirical study

The empirical study has a slight limitation to the german-speaking area. The platform XING is a professional network, which is mostly spread within the D-A-CH region (Germany, Austria and Switzerland)[438]. Nevertheless, it can be assumed, that some international perceptions on the research subject will be included, as the platform operator claims that the platform is used by people from over 200 countries.

Due to the heterogeneous backgrounds of actors within the field of Industry 4.0, the possibility of a distortion in responses could increase, as each sector has different requirements on the identified technologies and their functions. However, this aspect is calculated and acceptable, as the results of the survey will give a general overview of the average perception.

5.4 Statistical methods for the analysis of empirical study

After completion of data collection and preparation, the data analysis begins. The data analyzing process substantially comprises two tasks. The first task is a summary of the collected and processed data to conclusive tables and graphics. The second task includes the investigation of the transferability of the sample's results to the overall population.

5.4.1 Descriptive statistics

Descriptive statistics contains all statistical procedures to deal with the preparation and evaluation of the studied data set. Generalizations or conclusions on the entire population are a task of inductive statistics. The methods of descriptive statistics can be divided in univariate, bivariate, and multivariate techniques. The division is based on the number of examined variables.[439] Univariate procedures illustrate the absolute and relative frequencies in different diagrams, such as histograms and pie or bar charts. Using that, the researcher obtains insights into the data material and any existing data relationships. Contingency tables are among the most important bivariate methods, which investigate whether two nominally scaled variables are mutually dependent.[440] Multivariate methods include a variety of different procedures to analyze the relationships between multiple variables. For continuous variables, the most important statistical measures are the average value and dispersion degree.[441]

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[438] In comparison to the international business network *LinkedIn*.
[439] Cf. Berekoven et al. (2006), p. 197f.
[440] Cf. Sander, M. (2011), p. 191
[441] Cf. Kuß, A. (2011), p. 188f.

Within the analysis of the underlying empirical study, only univariate techniques have been applied to illustrate relationships of data. Multivariate methods could not be implemented due to the measurement level of the data (see chapter 5.6).

5.4.2 Inductive statistics

Inductive statistics procedures, on the one hand, are suitable for the verification of assumptions on the obtained sampling data material. On the contrary, they can be applied to check the reliability of the inference of values from sample data to values of the population. In addition, inductive statistics procedures are needed for the data analysis using multivariate techniques to determine the degree of fulfilling particular, necessary requirements of those techniques.

The working hypothesis is the starting point of the statistical test and, after the insight of experts, formulated in a specific factual context. To hedge the working hypothesis, it is negated in a statistical formulation and the resulting null hypothesis will become subject to a statistical test method.[442] For the interpretation of sample results, there are two different approaches: Estimates and tests. A very famous test is the Chi-square test. Depending on the study objective, there are various forms of a test application. A major application is the independence test of variables. Within this test, it is investigated whether two features are mutually dependent or independent.[443]

5.5 Results of the empirical study

In the following section, the results of the online questionnaire will be analyzed to be able to answer the third secondary research question and, thus, give information on technology potential. The results can be found in appendix 4, illustrated in diagrams. The execution of an inductive statistics procedure in the form of the Chi-square test was avoided, as the sample size was too small to make a significant statement.[444]

Overall, there have been 24 evaluable responses generated. Moreover, there were four responses, which could not be analyzed because of the inconclusiveness of data and seven partially answered questionnaires (dropouts), which also could not be evaluated. The quantitatively largest response could be generated within the first week. The amount of responses nearly met the expectations of the empirical study (30 expected responses) and, therefore, can be seen as success. Even though a quantitative percentage concerning the response rate could not be derived (see chapter 5.2), the results let

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[442] Cf. Berekoven et al. (2006), p. 230
[443] Cf. Sander, M. (2011), p. 207f.
[444] Cf. Meissner, J.-D.; Wendler, T. (2008), p. 276ff.

conclude that, on the one hand, the topic Industry 4.0 has certain relevance and on the other hand, on a high quality of the questionnaire. Eight participants expressed their desire to be informed on the results of the empirical study. The evaluation of the questionnaire took place using Microsoft Excel tools.

The heterogeneity of the target group (see chapter 5.3) was confirmed by the participants' information on their professional backgrounds. According to this, 16.7% of the experts are working within the wider field of industry as well as within the IT & Internet sector. 12.5% have their background in mechanical and plant engineering and 8.3% in telecommunications. Experts from electrical and precision engineering, automobile industry (OEM, supplier), aerospace, education & training, and consulting sector are all represented at 4.2%. One fourth of the participants stated that they have different professional backgrounds to the listed. The question on the company size of the participants could not deliver any more information on the experts as the experts where nearly distributed equally among all company sizes (<10 = 17.6%, <100 = 11.8%, <1000 = 23.5%, <10.000 = 23.5%, >10.000 = 23.5%).[445] Almost one-third of the experts (31.6%) work in the IT department. This is the largest group of experts according to the allocation of departments. 15.8% are within the procurement & logistics department, and 10.5% of the experts work for the research & development and the sales department. The smallest group work directly within the manufacturing department in their company (5.3%). 21.1% of the respondents work for other departments.[446]

Subsequently, the most relevant facts for each function will be summarized. Figure 16 presents the results on the first function "Provision of object information" to give the reader an idea of the questionnaires' form. 48% of the Industry 4.0 experts evaluate the influence of the function "Provision of object information" on end-to-end digital integration with "very high" and 42% with "high". Only 10% of the responses either were assessed to "middle" or lower influence. More than two-third of the respondents (75%) comment that this function has either "very high" or "high" practical relevance. 58% of the experts state that their already are technological solutions on the market to offer solutions or will penetrate it within the next three years. More than one-third claims that this function will reach market readiness in 3-7 years.

[445] This figures shed a light on the relevance of the topic for the entire bandwidth of companies.
[446] Experts from all-important departments are represented, which let assume a high quality of answers.

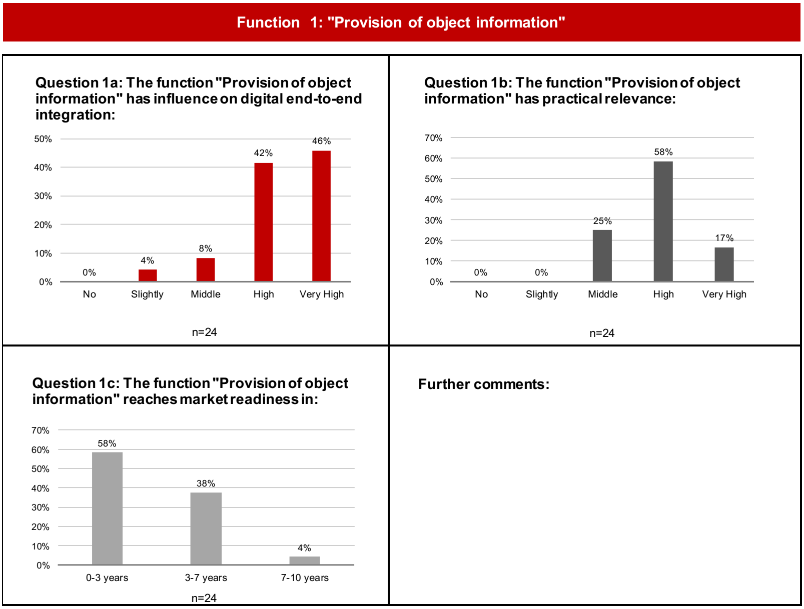

Figure 16: Exemplary illustration of results
(Source: Own representation)

A very clear statement on the influence on end-to-end digital integration was made on the function “Machine-to-machine communication.” More than two-third (67%) think that this feature has a “very high” influence. This estimation is confirmed by the practical relevance of this function. 92% state that “Machine-to-machine communication” has either “very high” (54%) or “high” (38%) relevance, when it comes to practical usage. The experts show a slight uncertainty on the market readiness of this function. 46% believe that it will be ready for the mass market in 0-3 years, and half of the experts think it will take at least 3-7 years until there will be developed technological solutions for this function. One expert stated that M2M will be able soon but has to be reconsidered according to its meaning (benefit or just a hype).
To the function “Energy provision”, half of the respondents only attribute a “middle” influence on end-to-end digital integration. Only 33% state that this function has a “high” influence and none of the respondents’ comment with “very high” influence. These figures are reflected in the practical relevance, where almost half of the experts (46%)

state that “Energy provision” has “middle” relevance. Even though the small impact of this function, 58% of participants state that there are already technological solutions on the market (0-3 years) or will be developed in near future (37%).

The function “Detection of own condition” was evaluated with 54% “high” and 25% “very high” influence on end-to-end digital integration. More than two-thirds of the respondents attribute a “very high” (29%) or “high” (42%) practical relevance to this function. The experts believe that this function can already be implemented on Intelligent Objects (58%) or will be developed within the next years (38%).

The “Detection of environment (context)” was attributed with a “middle” influence from more than half of the experts (54%). Still the experts claim that this function has a particular practical relevance (21% “high” and 25% “very high”). The market readiness of this function is evaluated to 58% with “3-7 years”. One-fourth even thinks that it will become mass market ready in “7-10 years”.

The function “Manipulation of the environment” was evaluated to 46% with a “slightly” and 42% with “middle” influence on end-to-end digital integration. 54% evaluate the practical relevance as “high” and exactly one-fourth of the experts with “middle.” Overall, 84% stated that this function is already or will reach market readiness within the next years.

“Data and information processing” functions of Intelligent Objects are seen as very influential on end-to-end digital integration. 84% of all respondents claim that it either has “very high” or “high” influence. This function, furthermore, is considered to have a “high” (58%) and “very high” (25%) practical relevance. Nearly half of the experts think that the technological solutions for this function already exist (46%) or will be developed within the next years, 3-7 years (50%).

The function “Human-machine interaction” is considered to have a “very high” influence to 54% and to 25% a “high” influence. This outcome correlates with the results of the practical relevance of the function. All 24 experts comment that it either has “Very high” or “High” practical relevance. These technological systems are perceived by 75% that they already exist or will be developed within the next three years. Whereas the influence of the function “Enhanced human machine interaction” is considered 54% with a “slight” impact on end-to-end digital integration. More than half of the experts (54%) claim that it merely has a “slight” practical relevance. Three-thirds of the participants of the questionnaire believes that it will take at least seven years to develop technologies, which enable this function.

The function “Autonomy of action” is attributed with a “high” influence on end-to-end digital integration of 46% and a “middle” influence of 38%. More than two-thirds of the experts (71%) evaluate its practical relevance as “slightly” or “middle.” This result correlates with its the market readiness of this function. Nearly all of the respondents (92%) think that it will reach market readiness in more than three or even seven years.

Nearly the same figures have been applied to the function “Cooperative autonomy of action”. 46% of the experts perceive its influence as “middle” and its practical relevance to 50% as “slight”. Clarity prevails on its market readiness. 71% state that this function cannot be implemented before seven years.

The function “Cognition”, 54%, was also evaluated with a middle influence on end-to-end digital integration. Its practical relevance is that 50% considered “slight” and its market readiness evaluated to 7-10 years with 67%. The function “Usage of digital integration platforms” was attributed with 67% with either “middle” or “high” influence on end-to-end digital integration and is perceived to reach market readiness in near future.

5.6 Reflection of research process

Within data collection and preparation, a variety of possible errors may occur.[447] The development of measuring instruments strikes for the highest possible measurement level. The higher the measurement level, the greater the density of information and the amount of existing statistical analyzing methods. Therefore, an attempt is made to use an interval scale. Hence, an interval scale for the execution of this empirical study could have been more appropriate. On the one hand, this has a particular legitimation, as many of the aforementioned statistical methods could not be applied for the data analysis (see chapter 5.4.1 and 5.4.2). On the other hand, this thesis does not claim to investigate already existing scenarios and their relationships in practice. It rather tries first to elaborate a “big picture” in an unexplored field. Thus, the data of an ordinal scale serves, as well as a purposeful method, to first derive findings and draw essential conclusions. Furthermore, it can be doubted, if the Industry 4.0 experts could make evaluations on metric measurement levels on the different functions (“function a is x times better than function b”). In terms of the execution of the online questionnaire, errors due to communication limitations have to be highlighted. These include specific strengths and weaknesses of each communication tool. The quality of collected data within online surveys is not a problem. Nonetheless, it has been found, during the analysis of the questionnaire, that some formulations and response possibilities within the questions could more precisely be defined. Exemplary, the response possibilities of the third question of each function can be taken as a negative expression. A more differentiated selection of response possibilities (e.g. “0-7 years” to “14-21 years”) could have been applied to avoid misleading assumptions. Moreover, it

[447] For a detailed overview on possible error types see Kuß, A. (2011), p. 158ff.

can be doubted if the explanations and the examples for each function have been sufficient to answer the questions appropriately.

6 Technology potential and recommendations for action

In this section, the results of the empirical study will be interpreted and consequently the technology potential of the key technology Intelligent Objects and its software-based and hardware-based technologies will be identified according to end-to-end digital integration. Furthermore, Intelligent Objects will be applied to technology paradigm in production logistics to illustrate possible chances of Intelligent Objects in this area. Based on the results recommendations for action will be elaborated.

6.1 Technology potential in production logistics

In the following, the technology potential will be developed and brought into contextual relationship to production logistics to answer the primary research questions.

6.1.1 Technology potential of Intelligent Objects

The empirical study gave meaningful information on technological potential of Intelligent Objects as well as on basic technologies, which are forming Intelligent Objects.

Overall, it can be concluded that the identified functions do have an influence on end-to-end digital integration and can be implemented in future production logistics environments. It also can be summarized that there is a positive correlation between the influence on end-to-end digital integration and practical relevance as well as a negative correlation between end-to-end digital integration and market readiness. The more influence a function is attributed to, the higher its practical relevance and the smaller the period of market readiness.[448] Differences among the identified functions have been analyzed in all three dimensions and will be described as follows to get a more detailed insight into the configuration of Intelligent Objects based on the results. In order to give the reader a better overview of the findings, a systematization into four groups was developed.

Altogether, there have been five functions evaluated with a majority (>78%) with either a “very high” or a “high” influence on end-to-end digital integration.

[448] Exact correlation coefficients could not be measured due to the chosen measurement level. An exact correlation has no a deeper meaning within the empirical study, which was aiming at first insight into an unexplored field.

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Huge technology potential (Group 1)			
	Xa	Xb	Xc
	"very high" and "high"	"very high" and "high"	"0-3 years" and "3-7 years"
Provision of object information	88%	75%	96%
Machine-to-machine communication	88%	92%	96%
Detection of own condition	79%	71%	96%
Data and information processing	84%	83%	96%
Human-machine interaction	79%	100%	100%

Figure 17: Functions with huge technology potential (Group 1)
(Source: Own representation)

All of these functions have also been evaluated to not less than 71% with a “very high” or “high” practical relevance and more than or equal to 96% with a market readiness in either “0-3 years” or “3-7 years”. The homogenous results of the empirical study are reason enough to attribute to these functions a huge technology potential as all three evaluation elements are rated among the highest values. This group makes the first group of functions and corresponding technologies and is considered to have huge potential when constituting Intelligent Objects (see figure 17).

The second group of functions is formed by functions, which have been evaluated to equal or more than 71% with “middle” or “high” influence on end-to-end digital integration (see figure 18). The functions “Energy provision”, “Detection of environment (context)” and “Usage of digital integration platforms” are attributed with a middle large technology potential. Because the experts evaluated these functions as to not less than 67% with a “middle” or “high” practical relevance, the technology potential nearly is as big as it is in Group 1. Hence, an intermediated level between huge and middle large potential has been introduced, named middle (high) technology potential. Due to the wider definition of energy provision, which includes external and internal energy sources, a distortion of results could have been aroused as, for example, energy-harvesting technologies could be hardly put on one level with traditional energy supply technologies such as batteries. An error in the research process in form of communicational aspects could lead to this result (see chapter 5.6). The function “Usage of digital integration platforms”, which often is promoted as the function with the most potential in Industry 4.0 literature, as well was evaluated “only” with middle (high) technology potential. This can have numerous reasons. An obvious factor might be the novel developments in the research field of integration platforms and the different interpretations and perspectives on the meaning of this function. In further research processes, a more differentiated explanation has to be considered. Overall, the technologies enabling these functions of group 2 are to more than 75% perceived to be ready for market penetration in less than 7 years.

Middle (high) technology potential (Group 2)			
	Xa	Xb	Xc
	"middle" and "high"	"middle" and "high"	"0-3 years" and "3-7 years"
Energy provision	84%	84%	96%
Detection of environment (context)	71%	67%	75%
Usage of digital integration platforms	77%	79%	84%

Figure 18: Functions with middle (high) technology potential (Group 2)
(Source: Own representation)

Within the third group, predominantly software-based functions are allocated. The corresponding technologies enable an autonomous and decentralized ability to make decisions without a central superior control system and thus are reflected by technological concepts of AI. All of these functions are evaluated with more than two-third of the answers (67%) with either a “middle” or a “high” influence on end-to-end digital integration. Due to their low practical relevance (>70% “slightly” or “middle”) and their market readiness, which is ranked among 3-7 years with prevailing majority on 7-10 years, the technology potential of the corresponding technologies only has a middle (low) technology potential concerning end-to-end digital integration. Especially these results are impressive; as it gets obvious that, a sole increase of software-based technologies, which enhance artificial intelligence, does not necessarily lead to a higher influence on the end-to-end digital integration of Intelligent Objects. The results are of interest in particular for further research questions, which explicitly deals with the question “How much intelligence is needed for which application?”.

Middle (low) technology potential (Group 3)			
	Xa	Xb	Xc
	"middle" and "high"	"slightly" and "middle"	"3-7 years" and "7-10 years"
Autonomy of action	84%	71%	92%
Cooperative autonomy of action	79%	79%	96%
Cognition	67%	75%	96%

Figure 19: Functions with middle (low) technology potential (Group 3)
(Source: Own representation)

Within the last group, the functions “Manipulation of environment” and “Enhanced human-machine interaction” are allocated. The functions are attributed with low technology potential and further more show inhomogeneous figures. Even though the function “Manipulation of environment” has only “slight” and “middle” influence on end-to-end digital integration, it has a “middle” and “high” practical relevance and is perceived to already be implemented on the market or will developed within the next few years. It can be concluded that the underlying technologies for this function are of small interest for the purpose of end-to-end digital integration but are used in various other applications. Enhanced human-machine interaction is considered not really to be pursuing end-to-end digital integration (54% “slightly”). It moreover is seen as function, which will reach market readiness in more than 7 years (75%). Hence, the technology potential of these functions is interpreted to be low (see figure 20).

Low technology potential (Group 4)

	Xa	Xb	Xc
	"slightly" and "middle"		
Manipluation of environment	88%	79%*	84%**
Enhanced human-machine interaction	79%	83%***	96%****

* "middle" and "high"
** "0-3 years" and "3-7 years"
*** "slightly" and "middle"
**** "3-7 years" and "7-10 years"

Figure 20: Functions with low technology potential (Group 4)[449]
(Source: Own representation)

Overall, it has to be summarized that Intelligent Objects in production logistics have a considerable technology potential, which strongly is dependent on the functions and technologies that are forming the Intelligent Object. A general conclusion on the technology potential of Intelligent Objects within this thesis would not lead to any new findings and results for practical use. It moreover would pursue an already existing ambiguous picture of Intelligent Objects.

6.1.2 Technology potential of technology paradigm

For the implementation of the previous evaluated functions and the corresponding technologies in production logistics a closer look on the technological systems, which support the fulfillment of planning, control and execution activities production logistics, is

[449] The functions have been grouped together based on the answers of Xa.

necessary. When applying Intelligent Objects in production logistics, new technology paradigm develop (see figure 13). According to Dosi's definition, technological paradigm are "models" and "patterns" of solutions of selected technological problems. This definition is based on Kuhn, who also attributes the existence of a concrete problem-solving component to a paradigm, which is used as idol or example (see chapter 2.1.2). To a high degree, this corresponds to the definition of the term "Technik" in Chapter 2.1.1, where it is defined as concrete manifestation and instrumentalization of a technology. As a distinction between "Technology" and "Technik" was renounced in this thesis, the use of the term technology paradigm is applied.

In Industry 4.0 literature, there are several scenarios described, which involve Intelligent Objects in production logistics. These technology paradigms are an application-specific manifestation of Intelligent Objects and developed around possible user-oriented functions (see chapter 2.2.1). The user-oriented functions strongly depend on the technology users' perceptions and desires of the benefits from Intelligent Objects. According to the target-means approach of technologies is gets clear that with the identified product-oriented functions (means) numerous user-oriented functions (targets) of an Intelligent Object in production logistics can be developed.

The technological configuration of technology paradigms in production logistics differs a lot from application to application and from user to user. Nevertheless, for the sake of practical relevance, 59 use-cases and research projects have been analyzed in order to figure out technology paradigm in production logistics (see list in the attachment) and to see, whether the identified functions of Intelligent Objects can be applied to the technology paradigm. The elaborations do not claim to be complete and cover the whole range of possible technology paradigm and corresponding user-oriented functions.

Within the investigations, four exemplary technology paradigms in production logistics have been identified, which are based on the presented field devices in chapter 3.3.2:

- **Intelligent conveyor system**
- **Intelligent commissioning system**
- **Intelligent production machine**
- **Intelligent load carrier**

For each of the identified technology paradigm five user-oriented functions have been derived based on their occurrence in the use-cases or research projects. The technology paradigm and it corresponding functions are listed up as follows:

Intelligent conveyor system:

- Recognition of load carriers
- Automatic loading/unloading
- Autonomous transport fulfillment
- Negotiation of transport orders
- Self-organization of system

Intelligent commissioning system:

- Visualization of information
- Navigation of employee
- Support on decision-making
- Quality control of picking
- Gesture recognition

Intelligent production machine:

- Self-reconfiguration
- Simulation of processes
- Planning of maintenance
- Negotiation of orders
- Autonomous order fulfillment

Intelligent load carrier:

- Constant traceability
- Recognition of transported goods
- Autonomous reorder of goods
- Negotiation with conveyor systems
- Energy autarkic transport

For the sake of practical relevance, the evaluated functions have been allocated to user demands (user-oriented functions) of the presented technology paradigms.[450] It can be concluded that the identified functions of Intelligent Objects to a high degree enable the functionality of user-specific demands on technology paradigms in applications from production logistics. The user's expectations on intelligent commissioning systems, for instance, are mostly based on human-machine interaction technologies. All of the

[450] In the appendix, an exemplary allocation is presented for each of the previously mentioned technology paradigm to illustrate the application-specific opportunities based on the identified functions of Intelligent Objects. The allocation has been executed based on the elaborations within this thesis. For a more detailed allocation, another empirical study on the user's demands would be reasonable.

identified user-oriented functions of intelligent commissioning systems are developed around this function. Thus, HMI technologies in this application have a considerable meaning. As this function was allocated among Group 1 with a huge technology potential (see previous chapter), it can be applied in future intelligent commissioning systems in order to support planning, control and execution activities in production logistics. Whereas the user's expectation on intelligent load carriers, have different characteristics. Intelligent load carriers mainly are developed based on functions and technologies, which imply a certain autonomy and decentralization such as the automatic reorder of goods. The function "autonomy of action" of Intelligent Objects also has technology potential concerning end-to-end digital integration even though it is not as huge as HMI solutions (Group 3, see previous chapter). Hence, intelligent load carriers could be equipped, depending on their special application, with, for example, software agents to fulfill activities autonomously based on the evaluation within the next 3-10 years based on the results of the empirical study.

6.1.3 Conclusion

Intelligent Objects in production logistics, which have been defined as practical reflection of CPS within the IoTS (see chapter 4.3), have based on the evaluation of Industry 4.0 experts and the underlying definitions for this thesis, a considerable technology potential. The extent of the technology potential in production logistics is driven by two characteristics, which have their origin in the target-means relationship of technologies (see chapter 2.2.2):

- **Application-specific demand on Intelligent Objects** (user-oriented functions)
- **Technological realization of Intelligent Objects** (product-oriented functions)

In this thesis, a foundation for the second characteristic was laid. Based on the technologies' functions, a technology potential of Intelligent Objects was elaborated. It furthermore was shown that Intelligent Objects do have a technology potential in production logistics in form of application-specific technology paradigm. In order to elaborate completely the technology potential of Intelligent Objects in production logistics further studies on the demand of technology user within production logistics are needed. First, exemplary expressions of technology paradigm were shown in the previous chapter to demonstrate technological feasibility of Intelligent Objects in production logistics.

The elaborated findings on the technology potential of Intelligent Objects and their underlying technologies are presented below in form of a function-based technology radar divided by their technological foundation (software-based or hardware-based).[451] The technology radar might constitute a profound orientation on the opportunities as well as on the challenges of Intelligent Objects when promoting end-to-end digital integration in a company. In order to have a more detailed overview about the technologies forming this functions, chapter 4 gives explicit information.

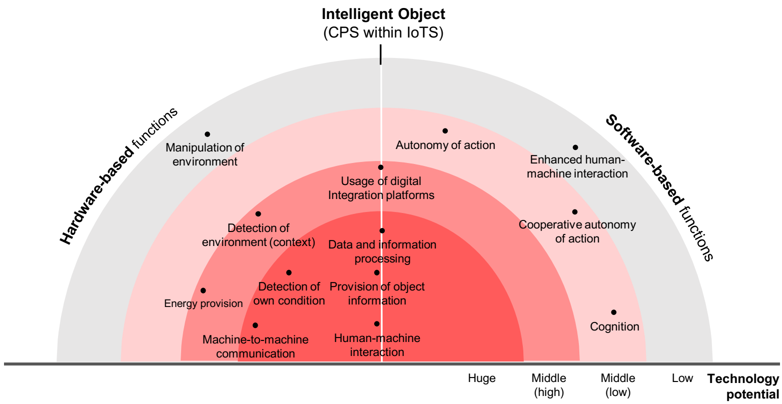

Figure 21: Function-based technology radar
(Source: Own representation)

6.2 Recommendations for action

In this section, recommendations for action for both technology supplier as well as technology user will be described based on the previous functions to answer the fourth secondary research question.

6.2.1 Technology supplier

At a closer look on the results of the empirical study and subsequently on the technology radar, currently Industry 4.0 experts predominantly perceive hardware-based functions and technologies to have the biggest technology potential on end-to-end digital integration. Technology supplier should focus on the development of technological solutions within this area in order to pursue business success in the short-term.

[451] The technology radar is based on the elaborations of this thesis and the underlying definitions of the involved terms. Most of the technologies need both hardware and software components to fully develop their potential. A separation was made in chapter 4 to have a systemized orientation within this thesis. The separation was made based on the origin of a function.

Nonetheless, software-based functions, which mostly have been evaluated with a middle large technology potential should as well be forced in manufacturing environments. Even though it will take, based on realistic estimations, a few years for prototyping and implementation and thus a contribution to business success. This fact on the other hand is also an advice to put more research efforts in software-intensive technologies, as the functions in fact mostly have also a high influence on end-to-end digital integration. The allocation to middle (high/low) technology potential simply is based on the evaluations of the practical relevance and the time for market readiness and thus the choice of evaluation criteria.

Within the field of hardware technologies, especially human-machine interaction and machine-to-machine communication technologies are attributed with particularly high influence on end-to-end digital integration. Technology supplier in the field of HMI systems, such as voice command and gesture recognition (see chapter 4.4.6) are well-advised to purse new technological solutions, as the interaction between employees and machines is considered to have a high influence on end-to-end digital integration in production logistics. According to the comment of an expert, some of HMI technologies do already exist for several years. This is undisputed; it is more about the development of these solutions in the manufacturing environment. Within the elaborations of technological functions, it was shown, that for example Microsoft's Kinect, which is a gesture recognition based gaming console, is already implemented on the consumer market very successfully. For technology supplier it is important to transfer this knowledge into industrial practice. An extension of human-machine interaction in order to develop technological systems with a kind of human awareness (enhanced human-machine interaction) are considered to have only slight practical relevance and thus have to be developed more user-oriented. In order to present its benefits technology supplier in this field are recommended to involve technology user within the development process. This user-centric approach ensures a development in line with market trends and demands.

Machine-to-machine communication technologies are to a huge extent also available on the market. Within this technology field, the focus should be set on the standardization of protocols, e.g. communication protocol such as OPC-UA and transportation protocol such as IP to pursue interoperability and thus develop complete functionality of this technology. To unfold the entire potential of a communication between Intelligent Objects and other technological systems, close cooperation between different, worldwide operating organizations, institutes and companies becomes necessary – in form of coopetition (see chapter 3.3). Coopetition as well is the main term, when it comes to digital integration platforms. The implementation of such technological constructs requires close business relationships between technology supplier (e.g. hardware such as cloud server as well as services based on software components) and technology user (e.g. usage of different services independently of its vendors). The development of data and information processing technologies can be seen two-fold. On the one hand, efficient microcontroller and high-performance processing components, which enable the actual processing of data and information, should be pursued. On the other hand, software-based advanced data analytics methods such as data mining can enhance the ability of Intelligent Objects in terms of decentralized decision-making and support of employees considerably. The function data and information processing is attributed with huge potential and thus has to be facilitated within the next years by technology supplier. Sensing and actuating technologies, which allow Intelligent Objects' the detection of own condition and context as well as the manipulation of the environment are considered to have different technological potentials. Whereas the developments of sensors, smart sensors and sensor networks open complete new opportunities in manufacturing environments as well as for the development of new business models, actuators are seen as important within industrial use but have no particular influence on end-to-end digital integration. As actuators are an essential component of mechatronics systems (see chapter 4.6), it though will be important to further develop this technology to meet the requirements of technology user in other application areas. Sensing technologies, which are the first source of data collection (plus possible data processing) have based on the evaluations of the experts huge technology potential and have to be brought into the market as soon as possible to foster business success of both technology user and supplier. Energy supply technologies of Intelligent Objects, esp. internal ones such as energy harvesting are perceived differently by academia and industry. Some authors claim that energy provision technologies that are locally installed on Intelligent Objects have huge importance to enable all other functions of Intelligent Objects. Hence, they indirectly have an influence on end-to-end digital integration and so have not less than huge technology potential as they are seen as necessary requirement for a complete functionality of Intelligent Objects. In practice, the experts see independently of the form of energy provision (internal or external)[452] middle large technology potential. The linkage between a vertical integration and the energy supply of the technological systems currently is not the focus of Industry 4.0 experts. Therefore, the developments at this technology field have to be approached from various perspectives and especially be treated as different technologies.

[452] A more detailed separation is suggested in further research initiatives.

The implementation of software agents in for example MAS at the current state is not perceived as practical relevant yet. Experts estimate that the development of market ready systems based on software agents will at least take 3-10 years. A complete decentralization and autonomy of Intelligent Objects filled with methods of AI is not necessary to become complete “digital integrated” and therefore both objectives should not be mixed up. Indeed the degree of intelligence of physical Objects influences the approach of a paradigm shift in production logistics (see chapter 3.2.4), but only has middle large potential for end-to-end digital integration. It can be concluded that end-to-end digital integration is a fundamental requirement for autonomy and decentralization but based on a “high degree” of intelligence a level of end-to-end digital integration cannot be derived. Technology supplier therefore are well advised to analyze the demand of its customer in order to avoid the development of “super” Intelligent Objects, which are intended to serve as replacements for human beings but in the end are implemented to fulfill simple activities or even completely replace manpower.

6.2.2 Technology user

For technology user in production logistics this thesis elaborated meaningful information. Among the process of technology and innovation management, technology user especially can derive essential information on Intelligent Objects as Industry 4.0 key technology, on basic technologies as well as on technology paradigms. In particular, an appropriate technology foresight and a technology evaluation based on own evaluation criteria can be planned and executed grounded on the findings from literature and the empirical study. The process of technology foresight in chapter 2 was described as pivotal to develop a profound technology strategy and thus ensure competiveness of a company. In that process, the foundations for decisions on future technological innovation activities of a company are laid.

By means of the results illustrated in the function-based technology radar, technology user are provided with a basis for future technology management processes concerning a digitalization of the company. In order to become “digital integrated” in future, technology user can choose different technologies based on their functions to form technology paradigm. The basic technological systems in production logistics nowadays, which were described in chapter 3.2.2, will also exist in future. They simply can be enhanced by new functionalities to support planning, control and execution activities depending on various requirements. New functionalities of those systems are enabled by basic technologies, which mostly already exist on the market. The interplay of these technologies through interconnection unfolds their entire potential. Industry 4.0 requirements such as real-time communication, decentralized control and interconnection beyond company borders will become technologically feasible with the presented functions.

Depending on the observation period of the technology strategy, Intelligent Objects in production logistics can be constructed around different functions and technologies. If a company currently is starting to boost their Industry 4.0 initiatives, for example by courtesy of technological innovations, first hardware-based solutions such as the provision of object information with classical Auto-ID systems can be implemented under consideration of cost aspects. The identification of physical Objects in literature as well as by Industry 4.0 experts is seen as vital component for an end-to-end digital integration. These systems are already proven on the market and can be implemented in projects with less than a few months. Assuming that the observation period of the technology strategy is short, the functions that are attributed with a huge technology potential can be implemented to realize short-term business success. Human-machine interaction, which can be enabled by various technologies and in different forms, for instance, might be adopted to many classical technological solutions in production logistics. These systems as well can be enriched with communication interfaces to pursue machine-to-machine communication based on industrial communications technologies such as WLAN. As a comment of an expert within the empirical study states: “The implementation of machine-to-machine communication technologies in production logistics is simply a question of reasonable usage. It is senseless to implement such technologies without any reason, just because it is a trend”. This statement can be applied to nearly each of the elaborated functions. Therefore, in chapter 6.1.2 the feasibility of the elaborated functions has been proved by means of examples of user-oriented functions from use-cases and research projects. It was shown that the implementation of Intelligent Objects in form of technology paradigm in production logistics is considerable, as many functions and technologies are needed to fulfill future customer demands on classical technological systems. In some cases, software-based functions such as the autonomy of action of Intelligent Objects is required in order to deliver complete functionality. According to the elaborations of this thesis, technology user are given important information to make profound evaluations on technologies based on AI. The technologies currently are not developed satisfactorily yet and it will take years to implement such technological systems with an adequate functionality in order to pursue end-to-end digital integration.

In essence, the recommendation of a certain technological selection forming an Intelligent Object in production logistics is not expedient for technology user. Technology user are provided with a basic elaboration on technological opportunities of Intelligent

Objects and in turn are advised to evaluate the presented technologies based on their own criteria. Hence, technology user are strongly recommended to define and express their demand on future Industry 4.0 technologies as Intelligent Objects only can be reasonably constructed by means of application specific requirements.

7 Summary and outlook

In the last section of this thesis, the present work is summarized and an outlook on possible future developments of Industry 4.0 technologies will be given.

7.1 Summary

The objective of this work was the elaboration of Industry 4.0 technologies and their corresponding potential regarding end-to-end digital integration in production logistics. The underlying criterion for the evaluation of technology potential were technological functions. In a first step, the theoretical background for a common understanding was described. The terms "Technology", "Technik" and "Technology paradigm" have been defined, classical technology classification models have been presented and the importance of technology and innovation management has been highlighted. The term function was defined and the meaningfulness of its nature for the evaluation of technology potential has been presented. The difference between product-oriented functions and user-oriented functions has been explained explicitly and set into a contextual relationship of this thesis. Hereby, the focus was set on product-oriented functions. Moreover, the theoretical background on production logistics was shown by means of its main planning, control and execution activities.

In chapter 3, the basis for all further elaborations was laid. Based on a literature review the concept of Industry 4.0 was explained in detail. Firstly, the main drivers of the concept have been presented followed by a definition of the term itself, its predicted economical potential and similar, international approaches. Within the three key features of the concept, the vertical integration by means of an end-to-end digital integration in a Smart Factory was explained and presented according to an envisaged dissolution of the automation pyramid in production logistics. The first research question was answered and an own definition of the term "end-to-end digital integration" was developed for the proceeding of the research process. Based on the previously defined scope of the thesis, Industry 4.0 technologies were identified. The key technological concepts CPS and IoTS were explained and brought into a tangible setting by means of its practical reflection - Intelligent Objects. By courtesy of a literature review based on the "snowball" method, product-oriented functions of Intelligent Objects were analyzed and allocated to either hardware-based or software-based basic technologies, which are forming Intelligent Objects. Overall, there have been identified 13 essential functions of Intelligent Objects, which might be implemented by various basic technologies. The elaborated functions and technologies were evaluated by Industry 4.0 experts within an empirical study to identify technology potential of the Industry 4.0 key technology Intelligent Object. The

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functions have been assessed based on three elements: influence on end-to-end digital integration, practical relevance and predicted market readiness. The results have shown that Intelligent Objects in general have a considerable technology potential. Especially hardware-based functions of Intelligent Objects such as the “Provision of object information”, “Human-machine interaction” and the “Detection of own condition” were attributed with a huge technology potential. Hence, basic technologies such as Auto-ID, HMI and sensors (e.g. sensor networks) are in particular suitable to pursue an end-to-end digital integration. Whereas, software-based functions such as the autonomy of action by technological means of MAS, which imply a higher intelligence of physical objects, were attributed with a middle great technology potential, as their practical relevance and their market readiness are not considered significant in near future. In order to illustrate a possible implementation of Intelligent Objects in production logistics, four exemplary technology paradigm such as intelligent load carrier and its user-oriented functions were analyzed by current use-cases and research projects. It was shown that the evaluated product-oriented functions to a high degree are needed to fulfill the demand on technology paradigm in production logistics. The results have formed a profound basis to derive recommendations for technology supplier and technology user.

7.2 Outlook

The findings of this thesis can serve as orientation model for Industry 4.0 initiatives with focus on technology implementation in future. The elaborations provide essential information in a quite unexplored field with numerous, different opinions and perspectives on technologies.

Intelligent Objects as practical reflection of CPS within the IoTS overall have a considerable technology potential regarding end-to-end digital integration in production logistics. It could be shown that different functions and its corresponding basic technologies have different influences on the path to a “digital integrated” company. In particular, the expectations of technology user of Intelligent Objects in production logistics have to be identified in future research initiatives. One of the main conclusions within this thesis was, that the degree of intelligence of physical objects does not necessary correlate with the influence on end-to-end digital integration. Hence, among all discussions on the development of “super” Intelligent Objects, the technological purpose of their implementation and their predicted benefits have to be taken into account. The addressed paradigm shift in production logistics have to be attributed to practical application fields, in which Intelligent Objects are attributed to the different planning, control and execution activities in production logistics. The planning processes, in future research initiatives, have to be considered in isolation, so that clear statements on the requirements of the intelligence of the technology paradigm can be made.

Furthermore, different evaluation criteria such as implementation and migration costs of Intelligent Objects and security issues should be taken into consideration in order to get a holistic view on the potential of the technologies.

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Appendices:

Appendix 1: Overview on identified technologies and functions

Appendix 2: Overview on addressed XING groups for empirical study

Appendix 3: Illustration online questionnaire

Appendix 4: Results of the online questionnaire

Appendix 5: Allocation of functions to technology paradigm in production logistics

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Appendix 1: Overview on identified technologies and functions

Key technology: **Intelligent Object**			
Number	Basic technologies (examples)	Product-oriented function	Description
1	Auto-ID Indoor GPS	**Provision of object information**	An Intelligent Object is always explicitly identifiable. Its position within a factory is always accurately localizable. Through a dynamic virtual copy, systems or users also get access to data and information that goes beyond the aforementioned information (e.g. historical production data).
2	LAN OPC-UA IP	**Machine-to-machine communication**	An intelligent Object is able to interact at any time with its environment (other technological systems) to exchange data and information by means of a communication interface.
3	Internal supply External supply	**Energy provision**	An Intelligent Object may be supplied with energy either internally or externally. External methods include inductive energy supply. Internal energy provision may be implemented either with an energy source, which have to be charged at regular intervals or by means of the self-generation of energy from the environment. The Intelligent Object would be energy self-sufficient and could save energy if necessary.
4	Sensors	**Detection of own condition**	An Intelligent Object is able to detect physical measuring variables by means of sensors. It furthermore is able to and convert the electrical signals into data. Typical measuring variables are, for instance, of thermal nature such as temperature.
5	Wireless sensor networks	**Detection of environment (context)**	An Intelligent Object is able to detect physical measuring variables on its environment (context) by means of, for example, sensors networks. Context relevant detection includes the amount of data and information that is important for the characterization of a situation and of a relationship between people or objects in a defined environment.
6	Actuators	**Manipulation of environment**	An Intelligent Object is able to manipulate the physical world by means of actuators. It is able to convert electrical signals of, for example, the information processing unit, into mechanical variables such as movements.

7	Microcontroller Data mining methods	**Data and information processing**	An Intelligent Object is able to convert detected data in information, process it and then for example, provide the information to its environment (another object, employees). It makes no difference whether the processing of information takes place directly on the object (decentralized, local) or in a higher-level system (centralized, e.g. MES).
8	Input device Output device	**Human-machine interaction**	An Intelligent Object is able to interact with employees by means of user interfaces (human-machine interaction, HMI). The employee, for instance, is provided with context relevant data and information. At the same time, the Intelligent Object is able to record information from employees. Technologically this is realized by input devices such as touch screens and output devices such as displays.
9	Human modelling	**Enhanced human-machine interaction**	An Intelligent Object is able to recognize users' intentions and plans (e.g. feelings) and anticipate human behavior and thus aligns its actions accordingly.
10	Software agent systems	**Autonomy of action**	An Intelligent Object is able to make autonomously decisions in non-deterministic systems according to predetermined goals. It determines in a decentralized way with which behavior programs it wants to reach its goals. Such autonomy includes a (limited) decision-making autonomy and has self-controlling elements.
11	Multi agent systems	**Cooperative autonomy of action**	An Intelligent Object is able to cooperate and negotiate with other Intelligent Objects and thus is able to achieve a superior system goal. The group members harmonize their actions with each other, so that a problem is tackled strategically and solved in a jointly coordinated manner. This behavior enables a self-organization of a system.
12	Machine learning methods	**Cognition**	An Intelligent Object is able to draw conclusions based on former decisions and results. It is capable of learning and thus is able to self-optimize its behavior. This enables the Intelligent Object to fulfill complex planning tasks for a longer periods.
13	Cloud computing	**Usage of digital integration platforms**	An Intelligent Object is able to exchange data and information on digital integration platforms with any other participants by means of so-called services (supply and use). Here, it is conceivable that e.g. the original functions of an Intelligent Object, are enhanced by the use of services.

Appendix 2: Overview on addressed XING groups for empirical study:

- Expertenaustausch Produktion und Logistik
- Automatisierungstechnik
- Industry 4.0
- Industry 4.0 - Datengestützte Produktion & Logistik
- Informationstechnologie in der Logistik
- M2M - The Internet of things
- Smart Factory & Industry 4.0 Schweiz
- Enterprise 4.0
- M2M-Talk
- Predictive Analytics and Big Data
- Automation und Robotik
- MM MaschinenMarkt - Fachmedium und Community zu Themen der Fertigungsindustrie

Appendix 3: Illustration online questionnaire

Introduction:

Welcome to the online questionnaire as part of my Master thesis at the Technical University of Berlin and Tongji University in Shanghai, China.

In this thesis, the overall topic Industry 4.0 is addressed. The work focuses on the so-called Industry 4.0 technologies that are considered the fundament of the fourth industrial revolution. Within the elaborations, only those technologies are in the focus that might be implemented within a Smart Factory, in particular in production logistics.

The required and at the same time underlying conceptual understanding for an adequate answering of the questions, will be provided to you in advance. Answering the questions will take about 10 minutes of your time. If you are interested in the research results, please feel free to leave your contact details at the end of the questionnaire.

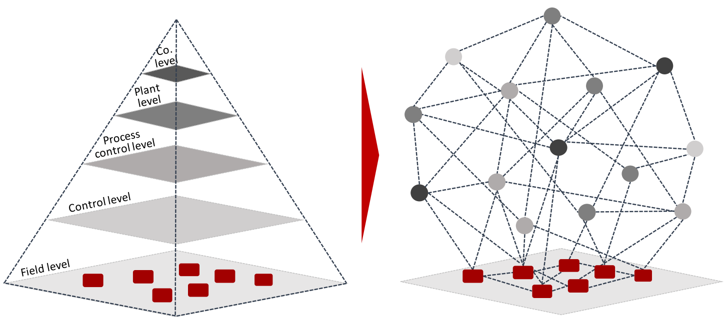
Subject of investigation:

The technological foundation of the fourth industrial revolution is formed by Cyber-Physical-Systems (CPS) and the Internet of Things and Services (IoTS). In current literature as well as in practice, these technologies are often described as Intelligent Objects and their application-specific manifestations – the technology paradigms (e.g. intelligent load carrier).

Within the thesis it will be examined, which functions of Intelligent Objects have an influence on end-to-end digital integration in a novel Smart Factory. In order to ensure a practical relevance of the investigations and thus to determine the technology potential of the technologies, it is also necessary to know whether the identified functions have a certain importance in your business. Moreover, the time period of market readiness of this functions is considered to form the technology potential.

<u>Conceptual understanding:</u> End-to-end digital integration

Current (IT) systems at different levels of the classic automation pyramid often are poorly or even not interconnected at all, so that there are limited flows of information. The systems are not able to reflect adequately the real situation in production (see graph, right). In a Smart Factory, the foundation for end-to-end digital integration should be laid. End-to-end digital integration implies a real-time capable, consistent, when required bidirectional flow of data and information between all involved, hetararchical structured technological systems within a Smart Factory in order to ensure planning, control and execution of productions logistics processes. This transformation enables an interconnection of strategic, tactical and operational levels in terms of a complete vertical integration (see graph, right).



<u>Conceptual understanding:</u> Function

The term function, according to DIN EN 1325 is defined as "[…] effect of a product or its components". The principle of function is particularly suitable as a criterion for analyzing a technology because it meets the following two purposes:

(a) Value assignment (technological efficiency)

(b) Translation of technology (market demand vs. technological feasibility)

The presented functions might influence each other to some extent or some features are implicitly available in other functions.

Evaluation methodology:

Please evaluate the 13 identified functions by means of an ordinal scale.

1	**Provision of object information** An Intelligent Object is always explicitly identifiable. Its position within a factory is always accurately localizable. Through a dynamic virtual copy, systems or users also get access to data and information that goes beyond the aforementioned information (e.g. historical production data). Examplary form of application: Digital product history

		No	Slightly	Middle	High	Very High
1a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
1b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
1c	The function reaches market readiness in:	○	○	○

Field for further comments

2	**Machine-to-machine communication** An intelligent Object is able to interact at any time with its environment (other technological systems) to exchange data and information by means of a communication interface. Examplary form of application: Notifictaion of own condition

		No	Slightly	Middle	High	Very High
2a	The function has influence on digital end-to-end integration:	◯	◯	◯	◯	◯

		No	Slightly	Middle	High	Very High
2b	The function has practical relevance:	◯	◯	◯	◯	◯

		0-3 years	3-7 years	7-10 years
2c	The function reaches market readiness in:	◯	◯	◯

Field for further comments

3	**Energy provision** An Intelligent Object may be supplied with energy either internally or externally. External methods include inductive energy supply. Internal energy provision may be implemented either with an energy source, which have to be charged at regular intervals or by means of the self-generation of energy from the environment. The Intelligent Object would be energy self-sufficient and could save energy if necessary. Examplary form of application: Energy harvesting

		No	Slightly	Middle	High	Very High
3a	The function has influence on digital end-to-end integration:	◯	◯	◯	◯	◯

		No	Slightly	Middle	High	Very High
3b	The function has practical relevance:	◯	◯	◯	◯	◯

		0-3 years	3-7 years	7-10 years
3c	The function reaches market readiness in:	◯	◯	◯

Field for further comments

4	**Detection of own condition** An Intelligent Object is able to detect physical measuring variables by means of sensors. It furthermore is able to and convert the electrical signals into data. Typical measuring variables are, for instance, of thermal nature such as temperature. Examplary form of application: Fault detection

		No	Slightly	Middle	High	Very High
4a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
4b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
4c	The function reaches market readiness in:	○	○	○

Field for further comments

5	**Detection of environment (context)** An Intelligent Object is able to detect physical measuring variables on its environment (context) by means of, for example, sensors networks. Context relevant detection includes the amount of data and information that is important for the characterization of a situation and of a relationship between people or objects in a defined environment. Examplary form of application: Exploration of production capacity of a machine

		No	Slightly	Middle	High	Very High
5a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
5b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
5c	The function reaches market readiness in:	○	○	○

Field for further comments

6	**Manipulation of environment**
	An Intelligent Object is able to manipulate the physical world by means of actuators. It is able to convert electrical signals of, for example, the information processing unit, into mechanical variables such as movements. Examplary form of application: Gripping movement

		No	Slightly	Middle	High	Very High
6a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
6b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
6c	The function reaches market readiness in:	○	○	○

Field for further comments

7	**Data and information processing**
	An Intelligent Object is able to convert detected data in information, process it and then for example, provide the information to its environment (another object, employees). It makes no difference whether the processing of information takes place directly on the object (decentralized, local) or in a higher-level system (centralized, e.g. MES). Examplary form of application: Advanced calculations

		No	Slightly	Middle	High	Very High
7a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
7b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
7c	The function reaches market readiness in:	○	○	○

Field for further comments

8	**Human-machine interaction**
	An Intelligent Object is able to interact with employees by means of user interfaces (human-machine interaction, HMI). The employee, for instance, is provided with context relevant data and information. At the same time, the Intelligent Object is able to record information from employees. Technologically this is realized by input devices such as touch screens and output devices such as displays. Examplary form of application: Visualization of information

		No	Slightly	Middle	High	Very High
8a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
8b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
8c	The function reaches market readiness in:	○	○	○

Field for further comments

9	**Enhanced human-machine interaction**
	An Intelligent Object is able to recognize users' intentions and plans (e.g. feelings) and anticipate human behavior and thus aligns its actions accordingly. Examplary form of application: Human-machine work stations

		No	Slightly	Middle	High	Very High
9a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
9b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
9c	The function reaches market readiness in:	○	○	○

Field for further comments

10	**Autonomy of action**
	An Intelligent Object is able to make autonomously decisions in non-deterministic systems according to predetermined goals. It determines in a decentralized way with which behavior programs it wants to reach its goals. Such autonomy includes a (limited) decision-making autonomy and has self-controlling elements. Examplary form of application: Self-control

		No	Slightly	Middle	High	Very High
10a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
10b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
10c	The function reaches market readiness in:	○	○	○

Field for further comments

11	**Cooperative autonomy of action**
	An Intelligent Object is able to cooperate and negotiate with other Intelligent Objects and thus is able to achieve a superior system goal. The group members harmonize their actions with each other, so that a problem is tackled strategically and solved in a jointly coordinated manner. This behavior enables a self-organization of a system. Examplary form of application: Self-organizing systems

		No	Slightly	Middle	High	Very High
11a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
11b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
11c	The function reaches market readiness in:	○	○	○

Field for further comments

12	**Cognition**
	An Intelligent Object is able to draw conclusions based on former decisions and results. It is capable of learning and thus is able to self-optimize its behavior. This enables the Intelligent Object to fulfill complex planning tasks for a longer periods. Examplary form of application: Self-learning systems

		No	Slightly	Middle	High	Very High
12a	The function has influence on digital end-to-end integration:	○	○	○	○	○

		No	Slightly	Middle	High	Very High
12b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
12c	The function reaches market readiness in:	○	○	○

Field for further comments

13	**Usage of digital integration platforms**
	An Intelligent Object is able to exchange data and information on digital integration platforms with any other participants by means of so-called services (supply and use). Here, it is conceivable that e.g. the original functions of an Intelligent Object, are enhanced by use of services. Examplary form of application: MES on platform

		No	Slightly	Middle	High	Very High
13a	The function has influence on digital end-to-end integration:	○	○	○	○	○

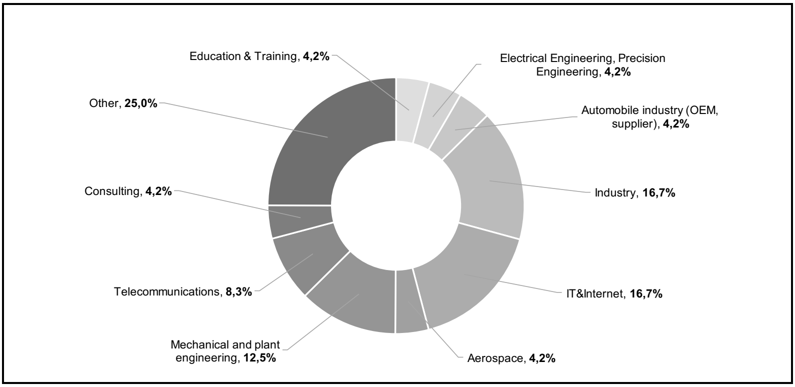
		No	Slightly	Middle	High	Very High
13b	The function has practical relevance:	○	○	○	○	○

		0-3 years	3-7 years	7-10 years
13c	The function reaches market readiness in:	○	○	○

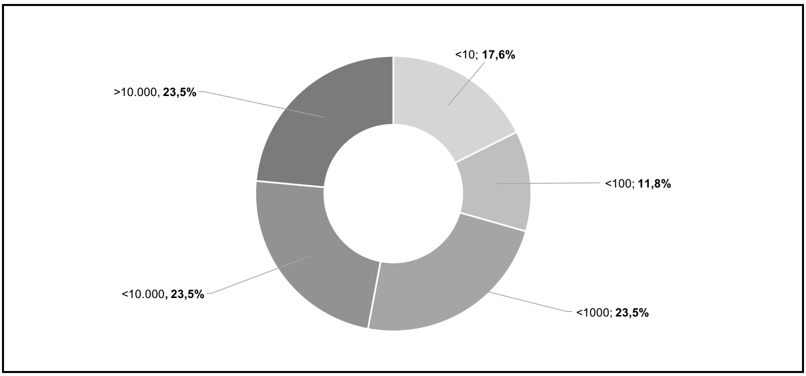
Field for further comments

Appendix 4: Results of online questionnaire

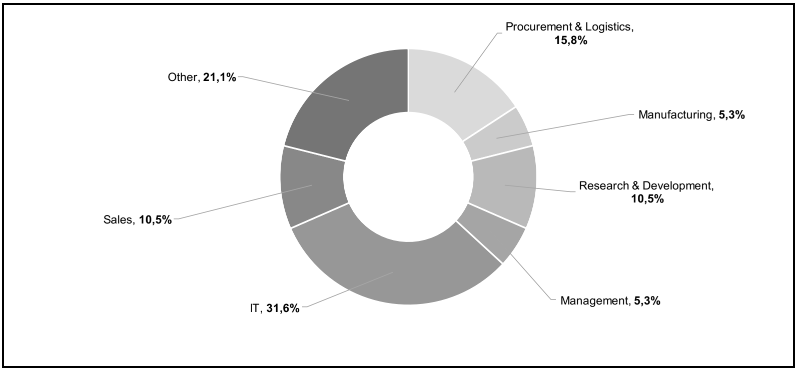
From which sector is the company you work at?



How many employees does the company for which you work have?

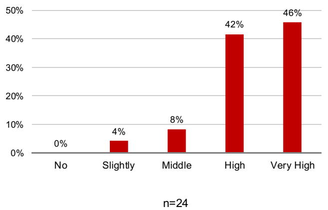


Which company department you work for?

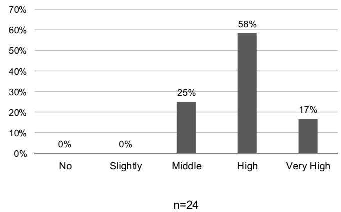


Function 1: "Provision of object information"

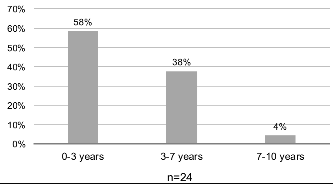
Question 1a: The function "Provision of object information" has influence on digital end-to-end integration:



Question 1b: The function "Provision of object information" has practical relevance:



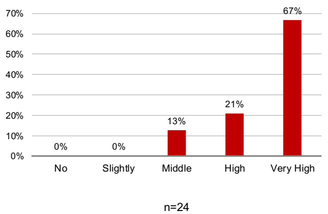
Question 1c: The function "Provision of object information" reaches market readiness in:



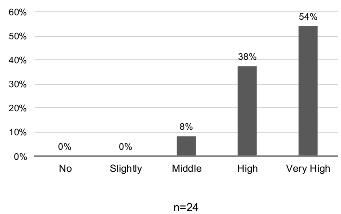
Further comments:

Function 2: "Machine-to-machine communication"

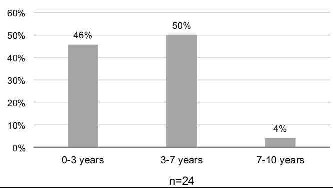
Question 2a: The function "Machine-to-machine communication" has influence on digital end-to-end integration:



Question 2b: The function "Machine-to-machine communication" has practical relevance:



Question 2c: The function "Machine-to-machine communication" reaches market readiness in:



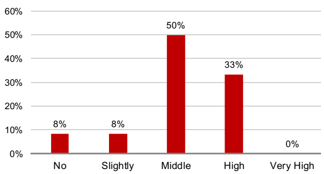
Further comments:

"Among the hype, one should always ask: Who communicates with whom? What does all the communication data mean? Does it have a special benefit or is it just modern and "in trend"?"

"Such systems already exist."

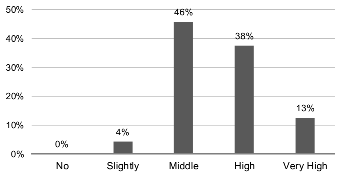
Function 3: "Energy provision"

Question 3a: The function "Energy provision" has influence on digital end-to-end integration:



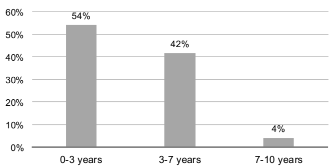
n=24

Question 3b: The function "Energy provision" has practical relevance:



n=24

Question 3c: The function "Energy provision" reaches market readiness in:



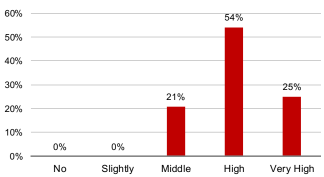
n=24

Further comments:

"Autarkic energy supply does already exist in practice. It strongly depend on the application, if it is needed.
Concerning a digital end-to-end integration, the erngy supply only might play a role, if the data ist centrally stored in a MES for example."

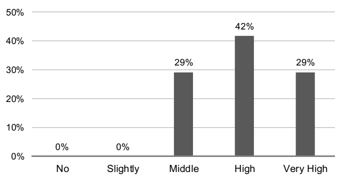
Function 4 "Detection of own condition"

Question 4a: The function "Detection of own condition" has influence on digital end-to-end integration:



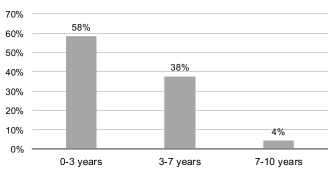
n=24

Question 4b: The function "Detection of own condition" has practical relevance:



n=24

Question 4c: The function "Detection of own condition" reaches market readiness in:



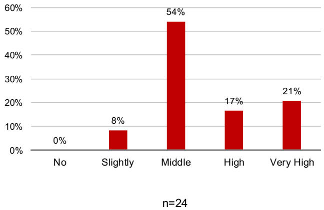
n=24

Further comments:

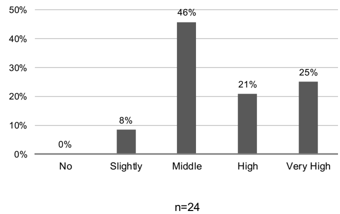
"In automation technology diagnostic systems are already existining. An famous example is Statie (Profibus).

Function 5: "Detection of environment (context)"

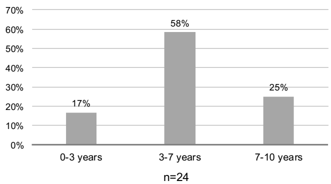
Question 5a: The function "Detection of environment (context)" has influence on digital end-to-end integration:



Question 5b: The function "Detection of environment (context)" has practical relevance:



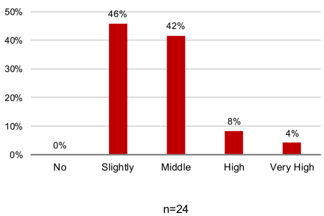
Question 5c: The function "Detection of environment (context)" reaches market readiness in:



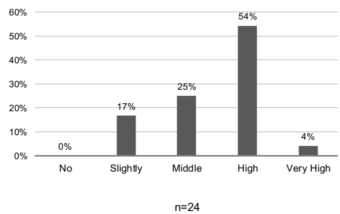
Further comments:

Function 6: "Manipulation of enivronment"

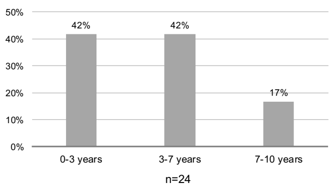
Question 6a: The function "Manipulation of environment" has influence on digital end-to-end integration:



Question 6b: The function "Manipulation of environment" has practical relevance:



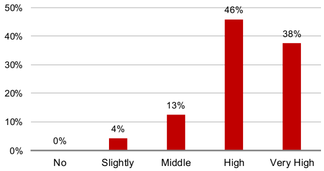
Question 6c: The function "Manipulation of environment" reaches market readiness in:



Further comments:

Function 7: "Data and information prossesing"

Question 7a: The function "Data and information prossesing" has influence on digital end-to-end integration:



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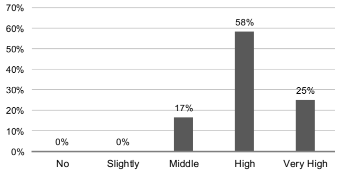
Question 7b: The function "Data and information prossesing" has practical relevance:



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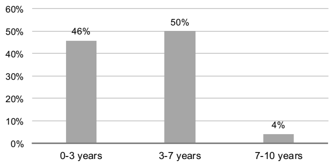
Question 7c: The function "Data and information prossesing" reaches market readiness in:

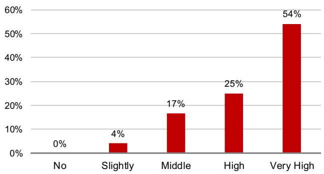


n=24

Further comments:

Function 8: "Human-machine interaction"

Question 8a: The function "Human-machine interaction" has influence on digital end-to-end integration:



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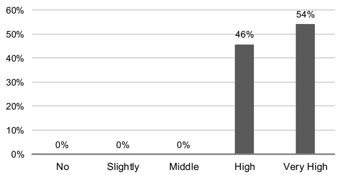
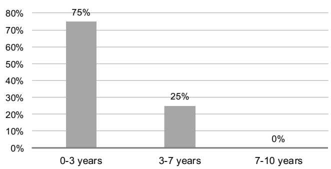
Question 8b: The function "Human-machine interaction" has practical relevance:



n=24

Question 8c: The function "Human-machine interaction" reaches market readiness in:



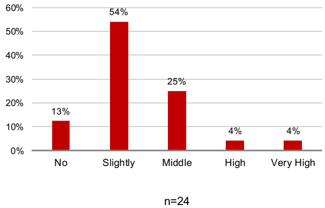
n=24

Further comments:

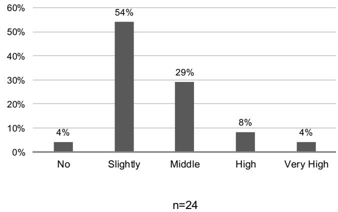
"HMI systems exist already for many man years."

Function 9: "Enhanced human-machine interaction"

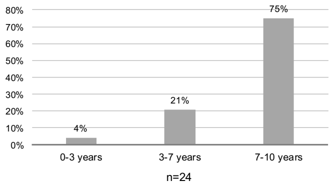
Question 9a: The function "Enhanced human-machine interaction" has influence on digital end-to-end integration:



Question 9b: The function "Enhanced human-machine interaction" has practical relevance:



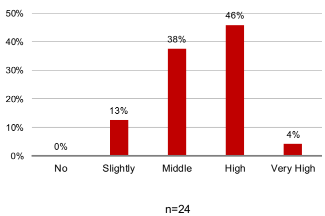
Question 9c: The function "Enhanced human-machine interaction" reaches market readiness in:



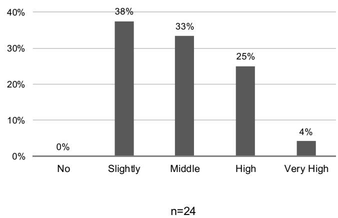
Further comments:

Function 10: "Autonomy of action"

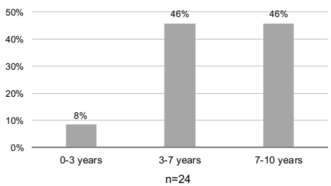
Question 10a: The function "Autonomy of action" has influence on digital end-to-end integration:



Question 10b: The function "Autonomy of action" has practical relevance:



Question 10c: The function "Autonomy of action" reaches market readiness in:

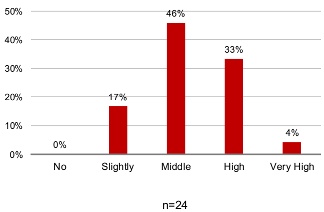


Further comments:

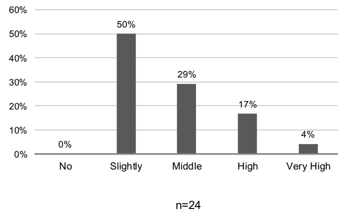
"Origin in automation technology. The degree of autonomy depends on the application."

Function 11: "Cooperative autonomy of action"

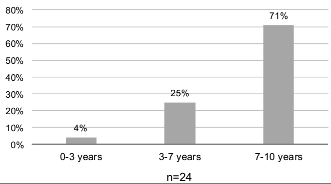
Question 11a: The function "Cooperative autonomy of action" has influence on digital end-to-end integration:



Question 11b: The function "Cooperative autonomy of action" has practical relevance:



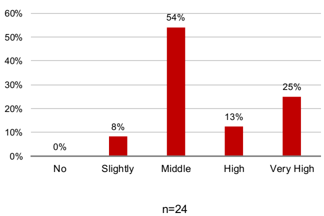
Question 11c: The function "Cooperative autonomy of action" reaches market readiness in:



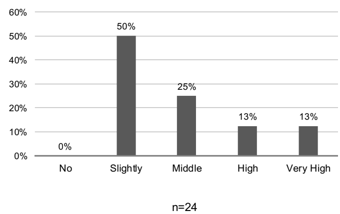
Further comments:

Function 12: "Cognition"

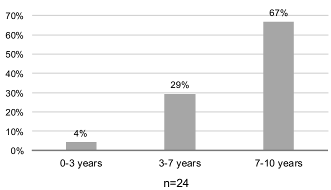
Question 12a: The function "Cognition" has influence on digital end-to-end integration:



Question 12b: The function "Cognition" has practical relevance:



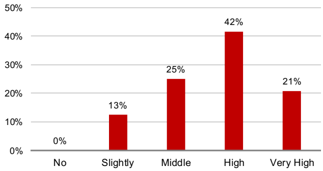
Question 12c: The function "Cognition" reaches market readiness in:



Further comments:

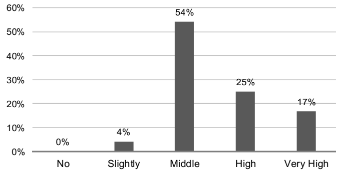
Function 13: "Usage of digital integration platforms"

Question 13a: The function "Usage of digital integration platforms" has influence on digital end-to-end integration:



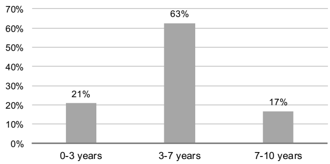
n=24

Question 13b: The function "Usage of digital integration platforms" has practical relevance:



n=24

Question 13c: The function "Usage of digital integration platforms" reaches market readiness in:



n=24

Further comments:

"The feature "overkill" has to be avoided.
The provision of functions from a PLC in the Internet can make sense in manufacturing, but does it not necessary."

Appendix 5: Allocation of functions to technology paradigm in production logistics

Use-Cases (literature)		Source	Application
Number	Description	Source	Application area
1	Intelligente Fabrik – vernetzte, adaptive und echtzeitfähige Produktion (Szenario 1: Auftragsabwicklung Küchenkauf)	Geisberger, Broy (2012)	Production
2	Intelligente Fabrik – vernetzte, adaptive und echtzeitfähige Produktion (Szenario 1: Produkt - und Produktionsprozes	Geisberger, Broy (2012)	Production
3	Selbstoptimierende Stanz-Biege-Maschine	Gausemeier et al. (2013)	Production
4	Mit flexiblen Maschinen unterschiedliche Produkte herstellen	Gausemeier et al. (2013)	Production
6	Intelligente Instandhaltung	Deindl (2013)	Production
7	Fallstudie 1 -Tracking-and-Tracing von Umverpackungen in der Konsumgüterindustrie	Deindl (2013)	Production logistics
8	Fallstudie 2 - Intelligente Vernetzung in der Produktion - Ladungsträger	Deindl (2013)	Production logistics
9	Fallstudie 2 - Intelligente Vernetzung in der Produktion - Gabelstapler	Deindl (2013)	Production logistics
11	Kanban-Bestellsystem beim Automobilhersteller	Schoch, Starsser (2003)	Production
14	Fallstudie – Automobillogistik (Containerlogistik) (Windelband)	Windelband et al. (2010)	Logistics
17	Schwarmintelligenz für die Logistik des Fraunhofer IML (Zellulare Transportsysteme - Multishuttle)	Günther, ten Hompel (2010)	Production logistics
18	Google Glass für die Kommissionierung	Günther, ten Hompel (2010)	Production logistics
19	CyProS – Anwendungsfall Intralogistik	Bauernhansl et al. (2014)	Production logistics
20	SEW Eurodrive - Von CIM über Lean Production zu Industrie 4.0	Bauernhansl et al. (2014)	Production logistics
21	Wandlungsfähige Produktionssysteme für den Automobilbau der Zukunft	Bauernhansl et al. (2014)	Production
22	Industrie 4.0-Fertigung im Siemens Elektronikwerk Amberg	Bauernhansl et al. (2014)	Production
23	MyJoghurt - Agentenbasierte dynamische Rekonfiguration von vernetzten intelligenten Produktionsanlagen	Bauernhansl et al. (2014)	Production
24	Enabling Industrie 4.0 – Chancen und Nutzen für die Prozessindustrie	Bauernhansl et al. (2014)	Production
25	Lemgoer Modellfabrik als Umsetzungsplattform von Industrie 4.0	Bauernhansl et al. (2014)	Production
26	iBin – Anthropomatik schafft revolutionäre Logistik-Lösungen	Bauernhansl et al. (2014)	Production logistics
27	Vom fahrerlosen Transportsystem (FTS) zur intelligenten mobilen Automatisierungsplattform	Bauernhansl et al. (2014)	Production logistics
28	ProSense - Produktionsplanung und -steuerung in einer INDUSTRIE 4.0	Bauernhansl et al. (2014)	Production
29	inBin - Intelligenter Kleinladungsträger (KLT) - Fraunhofer	Bauernhansl et al. (2014)	Production logistics
30	RFID- Handschuh in der Kommisionierung	Bauernhansl et al. (2014)	Production logistics
31	Augmented Reality - Unterstützung des Fahrers von Flurförderzeugen	Bauernhansl et al. (2014)	Production logistics
32	Agentenbasiertes Kommissioniersystem	Günthner, ten Hompel (2010)	Production logistics
33	Agentenbasiertes Staplerleitsystem	Günthner, ten Hompel (2010)	Production logistics
34	Reduktion des Energiebedarfs einer Karosseriebauanlage in produktionsfreien Zeiten	Kagermann et al. (2013)	Production
35	Telepräsenz - Fernwartung	Kagermann et al. (2013)	Production
36	Resliliente Fabrik	Kagermann et al. (2013)	Production
37	Intelligentes Instandhaltungsmanagement	Kagermann et al. (2013)	Production
38	Vernetzte Produktion	Kagermann et al. (2013)	Production
39	Selbstorganisierende adaptive Logistik	Kagermann et al. (2013)	Production logistics

Use-Cases (projects)		Source	Application
Number	Description	Source	Application area
40	Lemgoer Modellfabrik	Project	Production
41	Dyconnect	Project	Logistics
42	smaTRI	Project	Logistics
43	SmartFactoryKL	Project	Production
45	SemProM (Produkte führen Tagebuch)	Project	Production
46	BaZMod	Project	Production
47	CSC (Cyber System Connector)	Project	Production
48	CyPros	Project	Production
49	IWEPRO	Project	Production
50	KARIS PRO	Project	Production logistics
51	netkoPs	Project	Production logistics
52	pICASSO	Project	Production
53	ProSense	Project	Production
54	SCPS	Project	Production
55	SecurePLUGandWORK	Project	Production
56	SmartF-IT	Project	Production
57	EffektiV	Project	Production
58	SOPHIE	Project	Production
59	SmARPro	Project	Production logistics

Allocation of functions: Intelligent conveyor system

Key technology: **Intelligent Object**			Technology paradigm: **Intelligent conveyor system** — User-oriented function				
Number	Basic technologies (examples)	Product-oriented function	Recognition of load carriers	Automatic loading/unloading	Autonomous transport fulfillment	Negotiation of transport orders	Self-organization of system
1	Auto-ID Indoor GPS	Provision of object information	+	+	+	+	+
2	LAN OPC-UA IP	Machine-to-machine communication	+		+	+	+
3	Internal supply External supply	Energy provision	+	+	+	+	+
4	Sensors	Detection of own condition			+	+	+
5	Wireless sensor networks	Detection of environment (context)	+		+		+
6	Actuators	Manipulation of environment		+	+		+
7	Microcontroller Data mining methods	Data and information processing	+	+	+	+	+
8	Input device Output device	Human-machine interaction					
9	Human modelling	Enhanced human-machine interaction					
10	Software agent systems	Autonomy of action			+		+
11	Multi agent systems	Cooperative autonomy of action				+	+
12	Machine learning methods	Cognition					
13	Cloud computing	Usage of digital integration platforms					

Legend:

+ Product-oriented function is required to support user-oriented function

Allocation of functions: Intelligent commissioning system

Key technology: **Intelligent Object**			Technology paradigm: **Intelligent commissioning system** — User-oriented function				
Number	Basic technologies (examples)	Product-oriented function	Visualization of information	Navigation of employee	Support on decision-making	Quality control of picking	Gesture recognition
1	Auto-ID Indoor GPS	Provision of object information	⊕	⊕	⊕	⊕	
2	LAN OPC-UA IP	Machine-to-machine communication					
3	Internal supply External supply	Energy provision	⊕	⊕	⊕	⊕	
4	Sensors	Detection of own condition			⊕	⊕	
5	Wireless sensor networks	Detection of environment (context)			⊕		
6	Actuators	Manipulation of environment					
7	Microcontroller Data mining methods	Data and information processing	⊕	⊕	⊕	⊕	⊕
8	Input devices Output devices	Human-machine interaction	⊕	⊕	⊕	⊕	⊕
9	Human modelling	Enhanced human-machine interaction			⊕		⊕
10	Software agent systems	Autonomy of action					
11	Multi agent systems	Cooperative autonomy of action					
12	Machine learning methods	Cognition	⊕		⊕	⊕	⊕
13	Cloud computing	Usage of digital integration platforms					

Legend:

⊕ Product-oriented function is required to support user-oriented function

Allocation of functions: Intelligent production machine

Key technology: **Intelligent Object**			Technology paradigm: **Intelligent production machine** — User-oriented function				
Number	Basic technologies (examples)	Product-oriented function	Self-reconfiguration	Simulation of processes	Planning of maintanence	Negotiation of orders	Autonomous order fulfillment
1	Auto-ID Indoor GPS	Provision of object information	+	+	+	+	+
2	LAN OPC-UA IP	Machine-to-machine communication	+			+	+
3	Internal supply External supply	Energy provision	+	+	+	+	+
4	Sensors	Detection of own condition	+	+	+		+
5	Wireless sensor networks	Detection of environment (context)	+	+			+
6	Actuators	Manipulation of environment	+				+
7	Microcontroller Data mining methods	Data and information processing	+	+	+	+	+
8	Input device Output device	Human-machine interaction					
9	Human modelling	Enhanced human-machine interaction					
10	Software agent systems	Autonomy of action	+			+	+
11	Multi agent systems	Cooperative autonomy of action				+	+
12	Machine learning methods	Cognition		+	+	+	+
13	Cloud computing	Usage of digital integration platforms	+	+	+		+

Legend:

+ Product-oriented function is required to support user-oriented function

Allocation of functions: Intelligent load carrier

Key technology: **Intelligent Object**			Technology paradigm: **Intelligent load carrier** – User-oriented function: Constant traceability	Recognition of transported goods	Autonomous reorder of goods	Negotiation with conveyor systems	Energy autarkic transport
Number	Basic technologies (examples)	Product-oriented function					
1	Auto-ID Indoor GPS	Provision of object information	⊕	⊕	⊕	⊕	⊕
2	LAN OPC-UA IP	Machine-to-machine communication				⊕	
3	Internal supply External supply	Energy provision	⊕	⊕	⊕	⊕	⊕
4	Sensors	Detection of own condition		⊕			
5	Wireless sensor networks	Detection of environment (context)		⊕		⊕	⊕
6	Actuators	Manipulation of environment					⊕
7	Microcontroller Data mining methods	Data and information processing		⊕	⊕	⊕	
8	Input device Output device	Human-machine interaction					
9	Human modelling	Enhanced human-machine interaction					
10	Software agent systems	Autonomy of action			⊕	⊕	
11	Multi agent systems	Cooperative autonomy of action				⊕	
12	Machine learning methods	Cognition			⊕	⊕	
13	Cloud computing	Usage of digital integration platforms					

Legend:

⊕ Product-oriented function is required to support user-oriented function