Impact of digitalization on the strategic management of international manufacturing networks: A configurations perspective

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The President:

Prof. Dr. Thomas Bieger

Vorwort des Autors

Die vorliegende Dissertation entstand im Rahmen meiner Tätigkeit als wissenschaftlicher Mitarbeiter im Bereich für Produktionsmanagement am Institut für Technologiemanagement der Universität St.Gallen. Als Mitarbeiter im Team „Globale Produktion“ und Verantwortlicher für das Thema Digitalisierung hatte ich die Möglichkeit vielfältige Einblicke in zahlreiche produzierende Unternehmen und Branchen zu erhalten. Insbesondere zwei Benchmarking Projekte zum Thema Industrie 4.0 bzw. Digitalisierung sowie ein KTI Projekt dienen als Grundlage für diese Forschung. Daher möchte ich allen Industriepartnern und Projektbeteiligten für die hervorragende Zusammenarbeit und die wertvollen Ergebnisse herzlich danken. So konnte ich weitreichende und interessante Erkenntnisse aus den Projekten mitnehmen und mich persönlich sowie fachlich weiterentwickeln.

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St. Gallen im Oktober 2018 Christoph Benninghaus

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List of abbreviations

3D, 4D	three-dimensional, four-dimensional
3V	Volume, variety, velocity
5C	Connection, conversion, cyber, cognition, configure
AI	Artificial intelligence
AM	Additive manufacturing
AMT	Advanced manufacturing technology
AR	Augmented reality
B2B	Business-to-business
B2C	Business-to-customer
CAD	Computer-aided design
CAM	Computer-aided manufacturing
cf.	confer
CIM	Computer integrated manufacturing
CoE	Center of excellence
COO	Chief operating officer
CPS	Cyber-physical system
CTI	Commission for Technology and Innovation
e.g.	exempli gratia (for example)
DCV	Dynamic capabilities view
ERP	Enterprise resource planning
et al.	et alii
etc.	et cetera
FDI	Foreign direct investments
GPN	Global production network
GPS	Global positioning system
i.e.	id est (this means)
ICT	Information and communications technology
IoT	Internet of Things
IMN	International manufacturing network
IaaS	Infrastructure as a service
IT	Information technology
ITEM-HSG	Institute of Technology Management – University of St.Gallen

JIT	Just-in-Time
M2M	Machine-to-machine communication
MES	Manufacturing execution system
MNC	Multinational corporation
NASA	National Aeronautics and Space Administration
OEE	Overall equipment effectiveness
PaaS	Platform as a service
PLM	Product lifecycle management
R&D	Research and development
RBV	Resource-based view
RFID	Radio frequency identification
ROI	Return-on-investment
RQ	Research question
SaaS	Software as a service
SMART (product)	Simple, maintenance-friendly, affordable, reliable, timely-to-market
TIE	Technologies, innovation, entrepreneurship
TPM	Total productive maintenance
TQM	Total quality management
TRL	Technology readiness level
UAV	Unmanned aerial vehicle
US	United States
VDI	Verein Deutscher Ingenieure
VHB	Verband der Hochschullehrer für Betriebswirtschaft e.V.
VR	Virtual reality
WLAN	Wireless local area network

Cases

ASC	Automotive supply company
BEC	Building equipment company
CAC	Control & automation company
EEC	Electronic equipment company
HAC	Home appliances company
MTC	Machine tool company

Summary

Manufacturing operations are becoming increasingly global, which makes the management of distributed plants and the resulting international manufacturing networks even more challenging. In particular, manufacturing sites in high-wage locations are facing increasing competitive pressure not only externally within their industry, but also internally within their own manufacturing networks. A possible solution is often seen in the phenomenon of digitalization, which is expected to support factories in such locations and ensure a long-term competitive advantage. Digitalization is driven by various technological concepts and has become a central element in industry and daily-life. However, theory and practice only indicate how digitalization can improve performance levels from a single site perspective. Recent findings focus on plant levels and predominantly on technical aspects, but neglect developments and interdependencies in international manufacturing networks. Additionally, technologies are typically treated as fixed constraints and are not further reflected or specified.

The research at hand addresses the deficits of literature and practice and analyzes digital technologies that go beyond single locations and affect whole manufacturing networks. Thus, this thesis combines two fields of study that have been largely separated so far. Accordingly, it contributes to an improved understanding of the impact of selected digital technologies on plant roles and consequences for high-wage locations in manufacturing networks.

The thesis is structured into a theoretical, conceptual and empirical part. A review of scientific literature is followed by the identification of 30 technologies that are frequently mentioned in the context of digitalization. Afterwards, these technologies are defined, classified, sorted according to various filter criteria, and matched with different plant role typologies. In this context, a *lead* factory concept seems most prevalent for locations in high-wage countries. To provide rich empirical evidence, a multiple case study methodology with six cross-industry manufacturing companies is applied.

The research is rooted in the field of international operations management. The aim is to develop a holistic approach that supports international manufacturers in positioning their high-wage manufacturing plants in an aligned, competitive footprint. Specific management frameworks, models and recommendations are developed to advise manufacturing companies in managing digital technologies globally. This research sets the theories “resource-based view of the firm” and “dynamic capabilities view” as the basis to explain competitive advantage and productivity gains of companies that successfully implement and utilize digital technologies.

Zusammenfassung

Auf Grund der Globalisierung von Produktionsaktivitäten wird das Management von global verteilten Werken und den daraus resultierenden internationalen Produktionsnetzwerken zunehmend herausfordernd. Dabei stehen insbesondere Produktionsstandorte in Hochlohnländern nicht nur innerhalb ihrer Branche, sondern auch innerhalb des eigenen Produktionsverbunds unter erhöhtem Wettbewerbsdruck. Als umfassende Lösung wird häufig das Phänomen der Digitalisierung angeführt, um Werke an Hochlohnstandorten zu unterstützen und langfristige Wettbewerbsvorteile zu generieren. Digitalisierung wird durch verschiedene technologische Konzepte vorangetrieben und hat sich zu einem zentralen Element des täglichen Lebens und für die Industrie entwickelt. Allerdings wird bislang in Theorie und Praxis lediglich aus Sicht des Einzelstandortes untersucht, wie das Leistungsniveau durch digitale Technologien verbessert werden kann. Neuere Erkenntnisse konzentrieren sich vorwiegend auf die Standortperspektive und technische Aspekte, vernachlässigen jedoch Entwicklungen und Abhängigkeiten in internationalen Produktionsnetzwerken. Darüber hinaus werden Technologien in der Regel eher einseitig betrachtet und nicht angemessen reflektiert oder spezifiziert.

Die vorliegende Forschung befasst sich mit diesen Defiziten der Literatur und Praxis und analysiert digitale Technologien, die über einzelne Standorte hinausgehen und ganze Produktionsnetzwerke beeinflussen. So kombiniert diese Arbeit zwei bisher weitestgehend voneinander getrennte Forschungsströmungen. Damit trägt sie zu einem besseren Verständnis der Auswirkungen ausgewählter, digitaler Technologien auf die Rollen von Werken und die Folgen für Hochlohnstandorte in Produktionsnetzwerken bei.

Die Arbeit gliedert sich in einen theoretischen, konzeptionellen und empirischen Teil. Nach einer wissenschaftlichen Literaturrecherche werden 30 Technologien, die im Rahmen der Digitalisierung häufig diskutiert werden, identifiziert, definiert, klassifiziert und nach verschiedenen Filterkriterien sortiert. Anschliessend werden diese Technologien mit verschiedenen Standortrollentypologien abgeglichen. In diesem Zusammenhang erscheint ein Leitwerk Konzept für Standorte in Hochlohnländern am relevantesten. Fallstudien mit sechs produzierenden Unternehmen bilden die Empirie der Arbeit.

Das Ziel ist es einen ganzheitlichen Ansatz zu entwickeln, der produzierende Unternehmen dabei unterstützen soll, ihre Hochlohnstandorte in einem angepassten, wettbewerbsfähigen Umfeld zu positionieren. Dazu werden spezifische Management-Frameworks, Modelle und Empfehlungen abgeleitet. Im Zuge dieser Forschung wird auf die Theorien “resource-based view of the firm” und “dynamic capabilities view” als Grundlagen zur Erklärung von Wettbewerbsvorteilen zurückgegriffen.

1 Introduction

1.1 Motivation and relevance

1.1.1 Practical relevance

"It is not the strongest of the species that survive, nor the most intelligent, but the one that is most responsive to change."
Charles Darwin

Not only species, but also future-oriented industries must anticipate upcoming changes and exploit the resulting opportunities faster than possible competitors. Firms need to adapt to the altering environment and re-think their strategies on a regular basis (Porter & Heppelmann, 2014). Apart from regional and economy-specific influences, various so-called megatrends have an impact on the future of manufacturing companies. Megatrends such as climate and demographic change, urbanization, individualization, mobility, or increasing standard of living are defining market requirements, whereas globalization, dynamic product lifecycles, technology diffusion, and limited resources (e.g. raw material) determine the way companies produce goods (E. Abele & Reinhart, 2011, p. 10; Bakker, Wang, Huisman, & Den Hollander, 2014, p. 10; Westkämper, 2013, p. 8). Globalization has gathered significant speed in the last decades (Cheng, Farooq, & Johansen, 2014, p. 161; Jacobi & Landherr, 2013, p. 23). This development is also reflected by the number of foreign direct investments (FDI), which have increased explosively since the 1970s (Cheng, Farooq, & Johansen, 2015). In 2016, global FDIs amounted to 1.746 trillion US-$ and it is expected that they will increase further (UNCTAD, 2017). These developments are mainly driven by developed or so-called high-wage countries, which have a share of 59 percent of global FDIs. In particular, manufacturing activities are becoming more international as this is the largest type of FDIs (Cheng, Farooq, & Johansen, 2011, p. 1311; Ernst & Kim, 2002, p. 1419; Ferdows, 1997a, p. 104).

Besides globalization advantages such as access to customers, new markets or resources, this progress has also downsides for high-wage countries. For example, high labor cost or regulatory provisions are ubiquitous challenges for manufacturers in high-wage locations (Y. Yin, Stecke, Swink, & Kaku, 2017, p. 67). Consequently, firms are outsourcing or offshoring production activities to lower-cost regions (Brettel, Friederichsen, Keller, & Rosenberg, 2014; Da Silveira, 2014; Martínez-Mora & Merino, 2014; Schmeisser, 2013). Especially, offshoring of manufacturing activities has been a serious concern for production sites in high-wage countries in recent years (Bertrand, 2011; Blinder, 2006, 2009; Dowlatshahi, 2005; Harrison & McMillan, 2011; Kinkel & Maloca, 2009; Kotabe, 1990; Rasheed & Gilley, 2005). For most companies the factor of cost differences (i.e. labor cost) is the main driver for offshoring or outsourcing manufacturing activities (Jacob & Strube, 2008, p. 9; S. Peters, Chun, & Lanza, 2016, p. 3). Other factors are the access to emerging markets and customer groups, lower transaction and transportation costs, as well as liberalized markets associated with fewer trade barriers. These factors as well as technological developments enable and accelerate the expansion of companies worldwide (Kenney, Massini, & Murtha, 2009; Schmeisser, 2013). Such activities result in the emergence and growth of complex international manufacturing networks (IMN) (Meijboom & Voordijk, 2003). Today, most existing manufacturing networks are a formation of individual and usually rarely planned decision-making (Kinkel & Maloca, 2009, p. 154). Ferdows (2014, p. 1) affirms that "it takes years to put them in place and it is difficult to change them quickly. Many variables […] affect the configuration of these networks and make it a challenge to control their evolution. Therefore, if well managed, a firm's production network can be a formidable source of competitive advantage; if not, it can significantly limit the firm's strategic options". Especially, factories in high-wage countries not only face competition within their industry, they rather compete with plants within their firm's IMN. Consequently, they need to clearly differentiate themselves from other sites within their respective network.

Cohen & Zysman (1987) argued that manufacturing activities are not disappearing but simply seeking new forms in high-wage countries. Thirty years later, it is obvious that these forms are dominated and driven by technology (Friedli, Benninghaus, & Elbe, 2017; Ketokivi, Turkulainen, Seppälä, Rouvinen, & Ali-Yrkkö, 2017; H. Lee, Lee, & Yoon, 2011; J. Martin & Mejean, 2014). The present situation demonstrates that manufacturing in high-wage countries is deeply rooted in technological innovations for products and processes (Nyhuis, Wulf, Klemke, & Hirsch, 2010, p. 231; Spring, Hughes, Mason, & McCaffrey, 2017, p. 6). Technological innovations in manufacturing are an essential enabler for business success and competitiveness either for provider or user companies (Sinha & Noble, 2008, p. 959; X. Wang & Zhang, 2014, p. 134). Nowadays, digitalization in form of digital technologies has become a global trend in industry and daily-life as it is embedded in products, services and operations of many firms (Brynjolfsson & McAfee, 2014, p. 58; Hagberg, Sundstrom, & Egels-Zandén, 2016, p. 694; Yoo, 2010, p. 213; Yoo, Boland, Lyytinen, & Majchrzak, 2012, p. 1398). The objective is an automated, customized production (UNCTAD, 2017, p. 181) at higher levels of productivity and operational efficiency (Bokrantz, Skoogh, Berlin, & Stahre, 2017, p. 154; Lu, 2017, p. 1; Wenking, Benninghaus, & Friedli, 2016, p. 847). In particular, companies in high-wage countries are digitalizing their processes, strategies, products, and structures by implementing technologies that are new to the organization. McKinsey & Company predict that productivity will increase by 26 percent and revenue by 23 percent as digital technologies will strongly change the manufacturing industry until 2025 (Wee, Kelly, Cattel, & Breunig, 2015).

Thus, nearshoring, reshoring, and onshoring are upcoming trends in Western Europe, which are precipitated by increasing digitalization and automation (Miebach Consulting GmbH, Müller-Dauppert, & Hoffmann, 2017; Strange & Zucchella, 2017; Tate & Bals, 2017). According to a benchmarking study conducted by the Division of Production Management at the Institute of Technology Management at the University of St.Gallen (ITEM-HSG), around 90 percent of the successful companies conduct digitalization activities to keep production in high-wage countries (Benninghaus, Lützner, & Friedli, 2016). However, hitherto, discussions regarding digitalization focus on a local or site level and do not consider the global perspective. This is quite surprising as the idea of digitalization claims a comprehensive and integrated connection of all systems, machines, humans, and objects worldwide.

Likewise Porter & Heppelmann (2014) and Bauernhansl (2014) argue that the concept of digitalization is of utmost importance to secure the competitiveness of manufacturing companies. Manufacturing will achieve the goal of "fastest time-to-market, highest quality, lowest cost, best service, cleanest environment, greatest flexibility, and high knowledge" (F. Tao, Zhang, & Nee, 2011, p. 4120). In addition, Brynjolfsson & McAfee's (2014) acclaimed book *The second machine age* highlights the benefits of digital technologies for the quality of work and the impact on industry and society.

Example: Automotive supplier

The enterprise operates several *lead* plants for different product groups in Germany, which collect information and gather experience in the context of digitalization. Internally, the enterprise calls them pioneering plants, which gives them a long-term strategic value for the overall manufacturing network. Hence, these *lead* plants are supporting the idea of future manufacturing and job security in high-wage countries. However, digitalization approaches are merely based on single site developments. According to experts of the enterprise, they cannot fully estimate how these technological developments change configuration, plant roles, responsibilities, and setup of their manufacturing network.

This and other examples show that companies are not considering the possible impact of technologically advanced sites on their IMNs and, accordingly, competences, responsibilities and plant roles in and for the network. Sendler (2018a, p. 44) summarizes the current challenges as follows: "Digitalization is a very clear example of how technical progress often – if not always – solves humankind's problems while, at the same time, more or less exchanging them for new ones”. Thus, it is both key enabler and future challenge for production in high-wage countries and entire manufacturing networks.

1.1.2 Scientific interest

Operations management research traditionally focuses on single manufacturing plants and only recently extended its perspective towards manufacturing networks (Brennan et al., 2015; Colotla, Shi, & Gregory, 2003; Feldmann, 2011; Rudberg & Olhager, 2003; Shi & Gregory, 1998). Nowadays, most companies are operating IMNs, which are outcomes of former offshoring, nearshoring, onshoring, reshoring (backshoring), merger and acquisitions, or sales activities. According to Kuehnle (2006, p. 53) “understanding network characteristics in production gives competitive advantages”. As IMNs have a significant impact on future performance, the strategic management of IMNs has become a central task for industrial companies (Bartlett & Ghoshal, 1989; Cheng et al., 2015; Ferdows, 1997a; Hayter, 1997). For example, Jacob & Strube (2008, p. 20) argue that “cost savings of between 20 and 45 percent can normally be captured from optimizing production networks”. Managers of manufacturing networks face strategic choices such as number and location of sites, product allocation to plants, technology transfer, strategic role of each plant, and coordination across factories (Vereecke & Van Dierdonck, 2002). Moreover, they must consider the dynamics and adapt the manufacturing network “according to emerging, internal and external events, developments and opportunities” (Papakostas, Georgoulias, Koukas, & Chryssolouris, 2015, p. 894). This also includes changes in process technology such as digital technologies (Ferdows, 2014, p. 3). Theory and practice show that these decisions are rarely planned – although, global networks “have become the world economy’s backbone and central nervous system” (Cattaneo, Gereffi, & Staritz, 2010, p. 7). In consequence, IMNs are typically fragmented and not optimally organized (Ferdows, 2014, p. 9). Additionally, manufacturing plants are often managed as “black boxes” (Cheng et al., 2011, p. 1315) and interdependencies are neglected (Cheng et al., 2015, p. 407). Clear plant roles and competences are not assigned to a factory and the benefits from high-wage and low-cost production are often not exploited (E. Abele & Reinhart, 2011, p. 121).

Referring to Brennan et al. (2015, p. 1262), “companies with their home base in high-wage countries such as Germany are also increasingly focusing on utilizing the strengths and potentials of their factories in their home base. We might see the beginning of a stronger imperative for local manufacturing in strategic markets […] and specialization of the necessary engineering and manufacturing competences”. In the following, manufacturing competences are internal abilities and unique skills stemming from successful practices, programs and initiatives (Koufteros, Vonderembse, & Doll, 2002, p. 257). Nonetheless, the influence of digital technologies on plants in high-wage locations and the IMN remains an unsolved issue. In fact, digitalization requires commitment across the whole firm and strategic planning as the application of modern technologies does not inevitably lead to an increase in efficiency or productivity (Benninghaus, Wenking, & Friedli, 2016, p. 78). However, most manufacturing companies still manage their digital transformation intuitively (Berghaus & Back, 2016, p. 12). In accordance, Strange & Zucchella (2017, p. 180) ask what will be future location advantages related to digitalization and will manufacturing tasks be reshored due to the technological developments?

The idea of this research is to study the effect of digital technologies on plant roles and IMNs. With reference to Ferdows (2018), this is a under-researched but at the same time highly relevant topic. Due to the advantages of digitalization, many companies are reviewing their location and "shoring" decisions (Tate & Bals, 2017, p. 106). Both streams, namely location decisions and plant roles, are relevant when describing the characteristics of a site (Szwejczewski, Sweeney, & Cousens, 2016). For example, the most recognized plant role typology was proposed by Ferdows (1997b). However, this popular "*lead* factory" approach barely addresses the management of technologies and therefore, it is unclear if a *lead* factory is still required or the position of this role is reinforced due to digitalization. Further, the effect of a changing plant role on other sites and the network as a whole is not examined (Cheng et al., 2011, p. 1312, 2015, p. 414; Feldmann, Olhager, Fleet, & Shi, 2013, p. 5696). Most scientific publications ignore the fact that each factory has an effect on other sites and cannot be treated separately (De Toni & Parussini, 2010, p. 3). Although "the management of technology on a global scale is moving higher on the research agendas of both academics and practitioners" (Medcof, 1997, p. 301), technology is not associated with IMNs in literature. Most scholars see technology as a "fixed system constraint", which is an obsolete simplification (Brennan et al., 2015, p. 1257). Researchers have to understand that digitalization needs more interdisciplinary research to address and reflect the topic appropriately (Legner et al., 2017, p. 307).

This thesis focuses on intra-firm networks and follows Bharadwaj et al.'s (2013, p. 480) call to address the role of digital technologies for companies from an internal view. Thus, the effect of adapted business models or smart products is not considered. Addressing the deficiencies of past research, this research seeks an integrated approach that on the one hand links the technological perspective to manufacturing sites and, on the other hand, derives the consequences for IMNs and high-wage locations.

1.1.3 Research gaps

The literature review and reflection of recent publications offer several research gaps. Although digitalization and management of IMNs have been discussed in literature for many years there are still deficits concerning an integral view. For example, digitalization has been investigated among others in different industries (Hess, Benlian, Matt, & Wiesböck, 2016; Liu, Chen, & Chou, 2011), its effect on business models (Loebbecke & Picot, 2015; Yoo, Henfridsson, & Lyytinen, 2010), consequences for management functions (Horlacher & Hess, 2016; Weill & Woerner, 2013), but not in the context of IMNs and across sites. Furthermore, many findings from other industries are not transferable to manufacturing companies, due to their different assets, product life cycle or investment periods compared to industries such as banking, retail or media. These deficits are the foundation for the present research.

First, most of existing literature merely treat technological potentials (e.g. Bokrantz et al., 2017) and technical issues (e.g. Thoben, Wiesner, & Wuest, 2017) of digitalization, but neglect the management context. The existing contributions ignore actual guidelines, drivers and allocation decisions. For instance, Chung (1996) emphasizes that the major obstacle to implementing new technology is not related to technology, but a human issue. Hence, a holistic view of the topic is lacking. Besides, discussions are mainly led by practitioners from industry or government and not from a scientific perspective.

Second, the effect of technologies on configuration decisions in manufacturing networks has not yet been investigated. Both topics are discussed independently in scientific literature streams. The link between new technologies and IMNs is under-researched (Ferdows, 2018, p. 398). Researchers consider technology as a fixed constraint, which is an obsolete simplification. Literature mainly shows how resources or digitalization can improve performance, competitive advantage and other factors from a single site perspective. This fact is not astonishing as many novel technologies are first implemented in one site and transferred to other sites in a subsequent step. But what are relevant digital technologies, which go beyond single locations and affect whole manufacturing networks? At present, it is not clear how the evolution of one plant due to digital technologies will affect other network locations and how this will lead to overall network changes (Cheng, Farooq, & Johansen, 2015, p. 403). Therefore, further research in this field is required. This research follows Ferdows' (2018, p. 398) call for investigating the impact of digital technologies on IMNs and is seen as a first attempt in this field.

Third, most of the research related to the strategic management of IMNs separates plant roles from the network level. Although the existing contributions regarding site roles are manifold, further research on plant roles is required (Ferdows, 2018, p. 393). Especially the impact of technology in general is barely considered. It is assumed that the alignment of plant roles is dependent on the strategy, but, on the other hand, on the existing processes, location, technology setup, etc. Especially Ferdows' (1997b) *lead* factory concept offers various potentials. Unfortunately, this site role typology is not conceptualized in the context of technology and digitalization decisions. Does a technologically enhanced site automatically become a *lead* site? What are responsibilities and tasks of such a *lead* factory? It can be assumed that a *lead* factory becomes a knowledge hub for the network, but what happens if the level of competences and responsibilities differs a lot across the sites? These effects need to be studied.

Fourth, the effect of digital technologies on high-wage locations is not considered in theory and practice. Pavitt (1990, p. 17) stresses "in high-wage countries, both the competitiveness of firms and more general welfare depend critically on the ability to keep up in innovative products and processes and in the underlying technologies". The research should identify how technologies that are new to a company potentially impact high-wage locations.

1.2 Terms and definitions

1.2.1 Manufacturing site

A manufacturing site is defined as the physical location of production and assembly functions, but also includes related activities such as sourcing or local process improvement. The term is used interchangeably with plant (e.g. De Toni & Parussini, 2010), factory (e.g. Ferdows, 1997b), subsidiary (e.g. Paterson & Brock, 2002), or facility (e.g. L. Chen, Olhager, & Tang, 2014). By extension, a site represents one element of a manufacturing network.

1.2.2 International manufacturing network

An IMN is generally defined as a formation of intra-firm sites or plants, which belong to one company and are located in different locations (worldwide). It extends the single site perspective towards the management of geographically dispersed manufacturing. Relevant aspects are manufacturing strategy, configuration and coordination within a network.

1.2.3 Technology & digitalization

This research defines technology as the deployment of technical and scientific knowledge that leads to the creation of goods or services. Digitalization is a recent form of technology and driven by various technological concepts. From an internal perspective, digitalization supports the improvement of process quality and efficiency, while external digitalization enhances products, services or creates entirely new business models.

1.2.4 Digital technology

Digital technologies are viewed as a combination of sensing, computing, memorizing, communicating, and performing abilities. These technologies have the potential to affect conventional manufacturing processes and strategies, firm capabilities, products and services, resources, as well as inter-firm relationships.

1.2.5 High-wage location

The definition of high-wage countries is not consistent in literature[1]. Following the classification of the World Bank, a high-wage country had a gross national income per capita above US-$ 12.736 in 2014 (Fantom & Serajuddin, 2016, p. 38). Although labor costs are the main characteristics, other aspects are also relevant when describing high-wage countries. In the context of this research, high-wage countries in Western Europe (i.e. Switzerland and Germany) are the object of study.

1.3 Research objectives

The deficits in theory and practice explain why there is still no holistic view that combines both digital technologies and configuration decisions from an IMN perspective. Based on the identified research gaps, a main research question (RQ) has been formulated. To fully address and explain coherences in more detail, three additional sub-RQs will be answered.

Table 1: Research questions (own illustration)

Main RQ: What is the impact of selected technologies on plant roles in high-wage locations in the context of international manufacturing networks?
Sub-RQ1: What digital technologies have the potential to impact plant roles in international manufacturing networks?
Sub-RQ2: How could the implementation of such technologies change the configuration in the context of international manufacturing networks?
Sub-RQ3: What are the consequences for high-wage locations and the management of international manufacturing networks as a whole?

[1] *Other notations are developed, high-income, high-cost, or industrialized country.*

The objective of this research is an examination of the impact of digital technologies on plant roles, IMNs and high-wage locations. In this context, helpful recommendations and solutions for problem solving are suggested. Further, frameworks and models are developed to support international manufacturers in managing their technological setups as well as positioning high-wage plants within their IMNs.

The purpose of sub-RQ1 is to examine dependencies between digital technologies and plant roles. In fact, to the best of the knowledge of the author, this is the first attempt to link two topics, which are typically discussed separately. The second sub-RQ discusses explicit changes of IMN configuration due to the implementation of selected digital technologies. The results from sub-RQ1 and sub-RQ2 serve as a basis to provide recommendations for high-wage locations and outline the consequences for whole IMNs (sub-RQ3). Since high-wage locations are part of the respective IMN, changes in a high-wage plant will at least theoretically affect the whole network footprint.

1.4 Research theory

The *resource-based view of the firm* (RBV) and the *dynamic capabilities view* (DCV) are employed as theoretical basis to understanding digital technologies in the context of IMNs. Both theories explain competitive advantages of companies. Since it was first mentioned by Penrose (1959) and further developed by Barney (1986a, 1986b, 1986c, 1988, 1991) and Wernerfelt (1984, 1995), RBV has become one of the most popular theories in research and especially for strategic management (Hitt, Xu, & Carnes, 2016, p. 78). RBV assumes that "sources of sustained competitive advantage are firm resources that are valuable, rare, imperfectly imitable, and non-substitutable. These resources include a broad range of organizational, social, and individual phenomena within firms that are the subject of a great deal of research in organization theory and organizational behavior" (Barney, 1991, p. 116). They can be drawn from the environment and combined in different ways to support a firm's activities (Wernerfelt, 1984). Referring to Teece, Pisano, & Shuen (1997, p. 516), "resources are firm-specific assets that are difficult if not impossible to imitate". In general, resources can be distinguished into tangible (e.g. financial or physical), intangible (e.g. reputation, brand, patents, know-how, or culture) or human resources (R. M. Grant, 2010, p. 127). In industrial industries, resources are input factors for the manufacturing process and can be seen as a weakness or strength of a company.

However, resources such as digital technologies do not inevitably lead to competitive advantages. Besides, also the ability to create sophisticated knowledge and anticipate future importance and value creation of resources is essential for creating competitive advantage (Barney, 1991; R. M. Grant, 1991). For example, Porter (1991, p. 108) argues that "resources are not valuable in and of themselves, but because they allow firms to perform activities that create advantages in particular markets. Resources are only meaningful in the context of performing certain activities to achieve certain competitive advantages". Consequently, resources need to be bundled to create a capability (Sirmon, Hitt, & Ireland, 2007). Thus, digital technologies, knowledge, infrastructure and related resources must be combined efficiently to achieve benefits.

Additionally, Eisenhardt & Martin (2000, p. 1106) conclude that RBV is not capable to explain long-term competitive advantage in dynamic and changing environments and markets. Hence, DCV builds on RBV and has provided complementary richness (Hitt et al., 2016, p. 79). Teece et al. (1997, p. 516) define "dynamic capabilities as the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments". Eisenhardt & Martin (2000, p. 1116) add that competitive advantage lies in their "ability to alter the resource base: create, integrate, recombine, and release resources". Accordingly, dynamic capabilities address the issue of developing, selecting and replacing resources. The term *dynamic* is related to a firm's ability to renew (technological) competences and the changing environmental conditions, which is typical for the manufacturing industry (Akhtar & Tabucanon, 1993, p. 265; Mediavilla, Martínez, & Mendibil, 2014, p. 86). *Capabilities* refer to the strategic management, which should be able to adapt, integrate as well as reconfigure internal and external competences, resources and knowledge to address these dynamics (Teece et al., 1997, p. 515). Although competences tend to have a technology respectively knowledge focus and capabilities consider business routines and process (Marino, 1996, p. 41), both terms are interchangeably addressed in this research.

Thus, most resources can only be a source of competitive advantage if they are transformed into real capabilities over time (Allred, Fawcett, Wallin, & Magnan, 2011, p. 130; Amit & Schoemaker, 1993, p. 35; Vaidyanathan & Devaraj, 2008, p. 409). Therefore, competitive advantage is basically a moving target, which is achieved by a series of temporary competitive advantages (D'Aveni, Dagnino, & Smith, 2010; Derfus et al., 2008). This can be achieved most likely by a recombination of existing resources or by acquiring or building up new resources (Bingham & Eisenhardt, 2011; Dierickx & Cool, 1989; Kor & Mahoney, 2004; Sirmon et al., 2007). Summarizing, "in situations involving dynamic and fast-changing environments, DCV explains firm competitiveness more effectively than RBV" (Lin & Wu, 2014, p. 407).

Referring to the RBV and DCV, digital technologies contribute to the competitive advantage of a company by first enlarging the resource portfolio and, second, by providing specific knowledge and capabilities. Competitive advantage is created due to enhanced production processes, which are shaped by digital technologies and specific technical knowledge. However, technologies cannot compensate poor manufacturing activities (Krafcik, 1988), but in combination with other capabilities such as TPM (total productive maintenance), TQM (total quality management) or JIT (Just-in-Time), a company can realize comprehensive gains in effectiveness and efficiency (Cua, Mckone, & Schroeder, 2001). The underlying theories support the idea that companies, which implement and apply digital technologies, have a competitive advantage on the site as well as on a manufacturing network level, if the resources and learnings are recognized and afterwards distributed across the IMN (Cavanagh & Freeman, 2012, p. 605). RBV and DCV also support the understanding of plant roles as an organizational network design element. While the RBV explains the bundle of resources (Cavanagh & Freeman, 2012, p. 614), which determine a plant role, DCV refers to the selection, development and implementation of technological capabilities to strengthen the position of a plant role. Therefore, digital technologies, plant roles and IMNs are manifold addressed by the combination of both theories.

1.5 Research design

This chapter focuses on the research design. First, the conceptual background as well as the generic research process is presented (1.5.1). Second, subsection 1.5.2 introduces a research framework, which illustrates the scope and context of this research. Finally, subsection 1.5.3 demonstrates the research methodology and explains how the RQs will be answered.

1.5.1 Conceptual background and generic research process

This research follows the understanding of management as applied social sciences research as introduced by Ulrich & Hill (1979). According to Ulrich (1984), it is defined as "[…] designing, controlling and further developing purpose-oriented socio-technical organizations" (cf. Rüegg-Stürm, 2005, p. 11). In this context, practical management problems of manufacturing companies in high-wage countries serve as the basis for this research. Thus, the aim is the development of a management framework for the design and application in practice in a socio-technical system. It is important to mention that the complexity and dependencies of such systems (e.g. technological system or manufacturing networks) are multitudinous and not fully controllable (Ulrich, 1984).

To improve the findings of this research process and minimize incorrect conclusions, research design and process are structured as a systematic, iterative and heuristic approach. According to Kubicek (1977) and Tomczak (1992) such a learning process is qualified for topics with limited existing knowledge and to derive concrete results in an iterative way (figure 1). Thereby, practical and theoretical knowledge of the author is continuously enriched by practical insights.

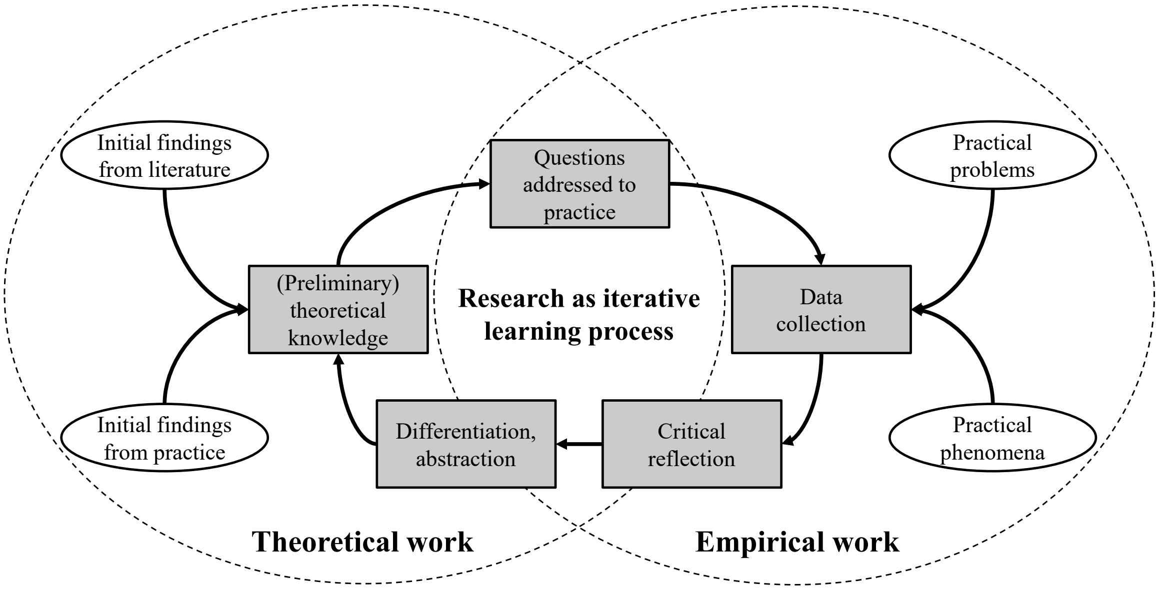


Figure 1: Iterative research process (adapted from Kubicek (1977, p.14), Tomczak (1992, p.84) and Baumbach (1998, p. 15))

The first step of the iterative approach is the creation of (preliminary) theoretical knowledge. In the context of this research project, this was achieved by initially screening the literature regarding IMNs, plant roles, technologies, and digitalization. Furthermore, first expert interviews were conducted to understand existing industry issues. These interviews were performed in the context of several industry and benchmarking projects with international operating companies from Germany and Switzerland. In a second step, the literature was analyzed in more detail (desk research) and RQs as well as gaps were defined. As mentioned before, these questions are addressing practically relevant issues.

Apart from a comprehensive literature review, several on-going and finished industry projects provided important information related to the RQs in form of multiple cross-industry case studies. Similarities and differences of the cross-industry cases were examined. This approach allows a continuous refinement and validation (Eisenhardt, 1989, p. 540,541). The critical reflection was initiated by conclusive expert interviews and discussions in a focus group. The results from all process steps were consolidated and evaluated. The final step of the iterative process was the differentiation and abstraction of the results that led to refined practical questions and recommendations for action.

Following Ulrich's idea, a research process begins and ends in practice (Ulrich, 1984, p. 192). The overall result of this research project are several management frameworks, which provide guidance for companies and plant managers in defining an advantageous setup of their high-wage location sites in accordance with the technological know-how and capabilities and assuring not only efficient production, but also a beneficial contribution to the whole manufacturing network.

1.5.2 Research framework

Kubicek (1977) defines conceptual schemes, conceptual frameworks, or frames of reference as propositional systems that do not meet strict requirements of hypothetical systems due to their logical consistence and usability. Figure 2 shows the preliminary research framework, which will be refined during this research (cf. chapter 6.3).

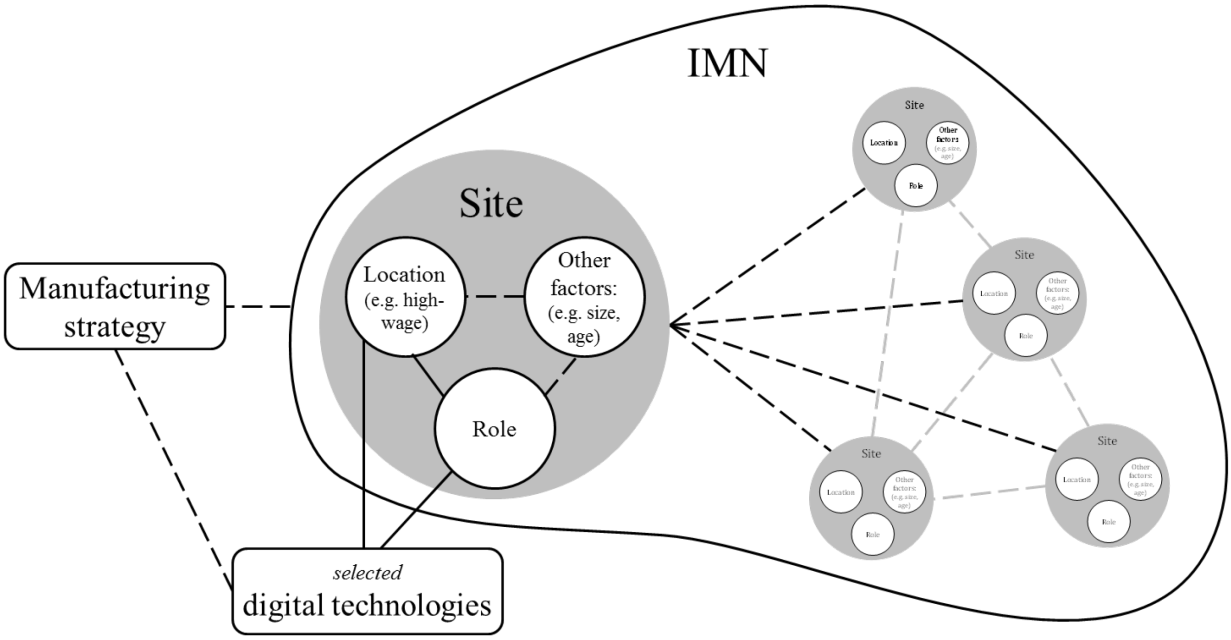


Figure 2: Research framework (own illustration)

A framework can be designed as a diagram consisting of check boxes and arrows (Kubicek, 1977, p. 17,18). In developing such a framework, research scope, relevant variables, important interactions, and the mechanisms behind them have to be identified (Porter, 1991, p. 98). Hence, a conceptual framework is an expression of certain theoretic fields and RQs, which is analyzed and adjusted continuously.

All relevant elements of this research project are presented in figure 2:

- *Sites*: The grey circles symbolize manufacturing sites. A manufacturing site is mainly characterized by its role, its location and additional factors such as size, capacity or age (history). The role depends on the chosen typology (see chapter 2.5). Location determines whether a plant is in a low-cost or high-wage country. The lines within the grey circle represent the interdependencies of the characteristics, whereas dependencies between the broken lines are neglected.
- *IMN*: A manufacturing site is linked to other factories in the manufacturing network (Cheng et al., 2011; De Toni & Parussini, 2010; Feldmann et al., 2013). The consequences of an altered plant role and the whole IMN are represented by the broken lines.
- *Digital technology*: Digital technologies are expected to have an impact on location decisions and plant roles. First, some digital technologies are commonly more utilized in high-wage countries than in low-wage regions and not all locations provide access to technologies. Second, plant roles are affected by technologies as the level of technological know-how and competences influence responsibilities. The research at hand will predominantly focus on these coherencies.
- *Manufacturing strategy*: Manufacturing strategy has an impact on manufacturing and network capabilities. Such a strategy sets the direction for plants, technology utilization, etc. It will be more detailed in chapter 2.2.

1.5.3 Research methodology

The consistency between RQs and the applied methodology is of major relevance to each research project (Saunders, Lewis, & Thornhill, 2009, p. 136). This research adopts an inductive approach, as the intention is to extrapolate from individual observations to general circumstances (Tomczak, 1992, p. 77). As there is only limited knowledge about *lead* factories and the influence of digital technologies on manufacturing networks, the topic is investigated with the help of qualitative social research in form of a multiple case study analysis.

With reference to Voss, Tsikriktsis, & Frohlich (2002, p. 197), case study research is especially informative for phenomena that "can be studied in its natural setting and meaningful, relevant theory generated from the understanding gained through observing actual practice". This is why multiple case studies are most suitable to explain the underlying research phenomenon in-depth. At first, it provides rich information in a field with limited knowledge due to the exploratory character (Voss et al., 2002, p. 197). It seeks for new insights and explores what is happening. Second, multiple case studies provide more accurate results and allow for more reliable generalization than single case studies (Eisenhardt, 1989, p. 542). If the cases differ in several terms such as industry, product, size, operations, etc. it can provide external validity and inhibits observer bias (Voss et al., 2002, p. 210). Third, qualitative case studies are advantageous for theory building due to open questions and general robustness (Eisenhardt & Graebner, 2007, p. 26; Yin, 2009, p. 53). Last, Yin (2009, p. 9) suggests that case studies are the best choice when trying to answer exploratory questions ("What?") or explanatory questions ("How?"). As all (sub)-RQs (table 1: research questions) belong to one of the two question types, the choice of methodology seems adequate. The research framework as well as the findings in chapter 3 serve as "theoretical propositions" for the author to support data collection (Yin, 2009, p. 18). Within the course of the study at hand, six cross-industry case studies were conducted with respect to *data* and *investigator triangulation*.

1.6 Thesis outline

The thesis is structured into seven chapters, detailing a conceptual, an empirical and a concluding part.

Chapter 1: Introduction

The current chapter presents an overview of the theoretical and scientific relevance and identifies several research gaps. Based on these gaps, a main and three sub-RQs are derived. Further, this chapter introduces the underlying research theory and design. It points out the initial research framework and the case methodology to answer the specific RQs.

Chapter 2: State of research

The subsequent chapter provides a review of the state of the art of IMNs. The relevant literature is analyzed systematically with the help of a three-step approach. The results of this screening process are summarized in the knowledge base on plant roles, locations, technology as well as digitalization. These findings allow for a revision of the RQs and gaps based on the results of the literature review.

Chapter 3: Interrelations of digital technologies and plant roles

The third chapter identifies and characterizes digital technologies in manufacturing. Following a funnel process, a few digital technologies are selected from the variety of existing technologies. These selected digital technologies are discussed in the context of different plant role typologies. As a result, a conceptual plant-technology-competence framework is derived.

Chapter 4: Empirical studies

Chapter 4 introduces the case research methodology. This chapter is the transition from the theoretical and conceptual stage to the empirical research. It explains the process of case selection and data collection. However, the main purpose of this chapter is the data analysis in form of six within-case studies. The case companies differ in terms of size, industry, technology portfolio, and manufacturing network setup.

Chapter 5: Cross-case analysis and discussion

The following cross-case analysis compares the case companies and identifies similarities as well as differences regarding the management and implementation of digital technologies. Furthermore, the literature is revisited to validate and sustain the findings.

Chapter 6: Implications for high-wage locations & management of IMNs

The outcomes of the previous chapters and especially of the empirical phase are generalized in chapter 6. On the one hand, the idea of this chapter is to improve the knowledge base on digital technologies in IMNs from a theoretical point of view. On the other hand, it tries to give practical recommendations and management implications.

Chapter 7: Conclusion and outlook

The final chapter summarizes the findings and contributions to theory and practice of this research. It also discusses the limitations of the research, which arise from the case research methodology and some content specific factors. An outlook with further research potentials concludes the thesis.

2 State of research

2.1 Strategic management

The basis for understanding IMNs is the strategic management discipline. With reference to Chandler's book *strategy and structure* from 1962, strategy is defined as "the determination of the long-run goals and objectives of an enterprise, and the adoption of courses of action and the allocation of resources necessary for carrying out these goals" (cf. R. M. Grant, 2010, p. 18). These strategic decisions should create options for future actions, which will shape the future success of a company. Main elements of a strategy are at first, *time horizon* and, second, *reference object*. In contrast to an operative and tactic time interval, a strategy has a long-term time horizon (minimum 5 to 10 years). Accordingly, strategic management requires a certain level of flexibility. The importance of flexibility increases with the length of the time horizon to which decisions are made as well as the dynamic and complexity of a company's environment. Second, the *reference object* refers to long-term planning of the product portfolio, acquisitions, technological orientation, mission statements, determination of concepts and relevant markets, etc. (Hungenberg, 2011).

In general, strategy can be delayered into industrial level strategies, corporate level strategies, business level strategies, and functional level (e.g. manufacturing, marketing, sales) strategies. For example, a corporate strategy builds on the outcomes of several functional strategies (Hill, 2000, p. 22). Thus, as proposed by Miltenburg (2009), manufacturing strategy is only one building block of the overall business strategy. As the focus of this research is on manufacturing networks, the following chapter concentrates on the manufacturing strategy.

2.2 Manufacturing strategy

Manufacturing strategy is a central element for the success of manufacturing companies. Although the topic is extensively discussed in literature there is no consistent definition of the term. Minor, Hensley, & Wood (1994), Dangayach & Deshmukh (2001), and Chatha, Butt, & Tariq (2015) provide comprehensive outlines of publications and definitions. Hayes & Wheelwright (1984, p. 32) propose that "manufacturing strategy consists of a sequence of decisions that, over time, enables a business unit to achieve a desired manufacturing structure, infrastructure, and set of specific capabilities". Miltenburg (2009, p. 6179) extends this view and states "manufacturing strategy is how a company uses its assets and prioritizes its activities to achieve its business goals. Manufacturing strategy depends on a company's industry and geographic location and is a pattern of competition that tries to generate competitive advantage". Thus, it can be seen as the linkage between the company's internal capabilities and external environment (Christiansen, Berry, Bruun, & Ward, 2003; Slack & Lewis, 2011). In this context, Ward & Duray (2000) have empirically shown that a poor fit is related to poor business performers. Skinner (1969, p. 145) argues that manufacturing becomes a "competitive weapon" for companies when the manufacturing strategy is aligned with the business strategy.

In fact, four basic elements are essential for developing a manufacturing strategy: manufacturing capabilities, structural and infrastructural levers, as well as network capabilities (cf. Boyer & Lewis, 2002; Christiansen et al., 2003; Fine & Hax, 1985; Friedli, Mundt, & Thomas, 2014; Hayes & Wheelwright, 1984; Hill, 2000; Leong, Snyder, & Ward, 1990; Menda & Dilts, 1997; Mills, Platts, & Gregory, 1995; Miltenburg, 2009, 2005; Rudberg & Olhager, 2003; Samson, 1991; Shi & Gregory, 1998). Whereas the prior categories have a long history in research, network capabilities were first mentioned by Shi & Gregory in 1998 and are not always part of a manufacturing strategy development or decisions. The following section gives an overview of the basic elements of a manufacturing strategy.

Manufacturing capabilities

A factory owns different capabilities or competences, which are needed to achieve the required level of performance. Table 2 presents the most recognized manufacturing capabilities from literature. A detailed discussion of these capabilities can be found in Sansone, Hilletofth, & Eriksson (2017).

Table 2: Manufacturing capabilities (Miltenburg, 2009; Sansone et al., 2017; Slack & Lewis, 2011)

Cost/Price		Ability to compete with competitors on low cost level
Quality	*Specification*	Extent to which product's features fully meet or exceed customer's requirements
	Conformance	Extent to which products are conform to specifications
Delivery	*Speed*	Meeting and even exceeding the expected delivery speed
	Reliability	Being reliable by keeping delivery promises on-time and in full
Flexibility	*Product range/ design flexibility*	Offering broad product ranges or ability to customize products to meet customer's expectations
	Order size/ delivery flexibility	Adapting order sizes or delivery times flexible to customer's needs
Innovation		Offering innovative products or products that enable the customer to be innovative
Service		Ability to provide services in addition to the core product

Ranking these manufacturing capabilities leads to competitive priorities which are success factors to meet the market requirements. For instance, Hayes & Wheelwright (1984, p. 40) define the concept of competitive priorities as strategic choices a company makes to compete in a market.

All these capabilities have a potential internal and external benefit. For example, high-performance in the *cost* category means externally low prices for the customers or internally higher margins. Higher performance in *speed* results in shorter external delivery times and faster response to customer requests, while internally the throughput times are shortened and overhead as well as processing costs are reduced (Slack & Lewis, 2011, p. 53). In this regard, several authors have discussed the link between competitive priorities, manufacturing competences, competitive advantage, and business outcomes (Bendoly, Rosenzweig, & Stratman, 2007, p. 259; Koufteros et al., 2002, p. 259; Leong et al., 1990, p. 111; Rosenzweig & Easton, 2010, p. 128; Rosenzweig & Roth, 2004, p. 355).

Network capabilities

IMNs are complex intra-company networks comprising several manufacturing sites with own capabilities (Miltenburg, 2009; Rudberg & Olhager, 2003; Shi & Gregory, 1998). Besides the heterogeneous competences of various sites, the overall network profits from specific capabilities, which derive from the configuration and coordination of the network. For example, the geographical dispersion of plants leads to access to specific markets, certain market information or low-cost labor. To extend the site perspective of a manufacturing strategy and cover holistic IMNs, network capabilities are more and more discussed in the course of manufacturing strategy development. In this context, Shi & Gregory (1998, p. 202) summarize *accessibility, thriftiness, mobility,* and *learning* as the four strategic network capabilities. In general, *accessibility* builds on the geographical distribution of sites and allows to reach different markets, customers, competitors, or suppliers. The access to strategic resources such as low-cost labor, external know-how, etc. also falls into this category (Shi & Gregory, 1998). *Thriftiness* is the ability to achieve economies of scope and scale as well as to reduce duplications of activities. Economies of scale describe the dependency of production volume on the input factors. Due to better utilization of equipment or standardization, the unit costs decrease with increasing production volume (Jacob & Strube, 2008, p. 3). Economies of scope occur "when for all outputs […], the cost of joint production is less than the cost of producing each output separately" (Teece, 1980, p. 224). The *mobility* capability provides the possibility to shift products, processes or personnel across an IMN. In addition, production volume and orders could be transferred. However, this requires similar products and processes at the plants (Colotla et al., 2003, p. 1191). Finally, *learning* represents the ability to explore and exploit internal as well as external knowledge. Internal knowledge comprises know-how regarding internal processes, best-practices or technologies. In contrast, external knowledge refers to market intelligence or customer expectations (Colotla et al., 2003, p. 1191; Friedli et al., 2014, p. 73; Shi & Gregory, 1998, p. 209).

Structural levers and infrastructural levers

Structural levers include all physical elements and the institutional arrangements within a plant. The structure relates to physical assets and configuration of resources (Hayes & Wheelwright, 1984, p. 392). Infrastructural levers comprise all activities within the boundaries of the structural levers (Hayes, Pisano, Upton, & Wheelwright, 2005, p. 41; Slack & Lewis, 2011, p. 29). Several scholars proposed sub-categories for both levers, which are presented in table 3. In reality, however, structural and infrastructural levers are overlapping and not separable (Colotla et al., 2003, p. 1187; Meijboom & Vos, 1997, p. 792).

Table 3: Structural and infrastructural levers (Rudberg & Olhager, 2003, p. 32; Friedli et al., 2014, p. 20)

	Hayes et al. (1984/2005)	Fine & Hax (1985)	Samson (1991)	Miltenburg (2005)	Skinner (1996)	Hill (2000)	Slack & Lewis (2002)
Structural levers							
Process technology	●	●	●	●	●	●	●
Capacity	●	●	●	●	●	●	●
Facilities	●	●	●	●	●	●	●
Vertical integration	●		●	●	●	●	●
Infrastructural levers							
Human resources	●	●	●	●	●	●	●
Organisation	●		●	●		●	●
Quality	●	●	●			●	●
Production planning and control	●		●	●	●	●	●
New product development	●	●	●				●
Performance measurement systems	●				●		

Both levers support the manufacturing and network capabilities. Therefore, the alignment of structural and infrastructural levers to the firm's priorities is of utmost importance. According to Hayes et al. (2005, p. 41) the levers are defined as follows:

- *Process technology (structure)*: Decisions regarding implemented technology, use of equipment, the degree of automation, or interconnections of (production) processes belong to this category. According to Yoo, Henfridsson, & Lyytinen (2010, p. 730), especially digital technologies are an "integral part of strategy formulations". They also have a huge impact on the specialization of plants and are therefore central aspects of this research.

- *Capacity (structure)*: This category comprises decisions regarding the amount, timing and type of manufacturing capacity, which may differ across the manufacturing sites.
- *Facilities (structure)*: Decisions are related to the location, size and specialization of plants.
- *Vertical integration (structure)*: This lever describes the direction, balance and extent of a firm's activities. The determination of relevant processes that are done internally (owned by the company) and how much will be purchased from suppliers is a central structural task.
- *Human resources (infrastructure)*: Decisions are related to the recruitment, selection, compensation, training, and employment security of employees.
- *Organization (infrastructure)*: All decisions regarding the organizational structure, the level of (de-)centralization and areas of responsibility belong to this category. The organization should be similar at different sites to simplify communication and exchange.
- *Quality (infrastructure)*: This category includes policies of internal quality management such as quality systems, monitoring or intervention.
- *Production planning and control (infrastructure)*: Decisions are associated with order handling, aggregate planning, scheduling of machines and workers, inventory management, etc. Also the degree of centralization of operations is a key aspect of production planning and control.
- *New product development (infrastructure)*: Decisions around the internal processes, structures and (technical) systems to develop new products fall into this category.
- *Performance measurement systems (infrastructure)*: Such tools are used to control and develop targets and performance. It comprises promotion policies, incentives (e.g. bonus) and other measures to achieve the firm's objectives. Usually it builds on the overall business strategy.

In conclusion, manufacturing strategy is one integral part of manufacturing networks. It defines the relevant competitive priorities and determines the structural and infrastructural levers to achieve a desired business outcome. Thus, the manufacturing strategy sets the operational scope and range of responsibilities of a company that needs to be aligned with other IMN dimensions (i.e. configuration and coordination) (Friedli et al., 2014, p. 45).

2.3 International manufacturing networks

2.3.1 Definition

Based on the development of internationalization and globalization theories in the 1960s, international manufacturing has evolved from global marketing and sales (Rudberg & Olhager, 2003, p. 29). In the 1970s, researchers were first focusing on plant level and not until the late 1990s did the first publications regarding IMNs emerge. Today, manufacturing scholars worldwide are investigating both, site and network level, as plants are viewed as a central part of network configuration and a basis construct of IMNs (Cheng et al., 2011, p. 1312; Feldmann et al., 2013, p. 5696).

An IMN is generally defined as “a coordinated aggregation (network) of intra-firm plants/factories owned by one company, but located in different places” (Cheng et al., 2015, p. 412). Therefore, it seeks to overcome the single site perspective towards the management of geographically dispersed manufacturing networks[2]. IMNs can be seen as a source of competitive advantage (e.g. Kuehnle, 2006, p. 53; Szász, Scherrer, & Deflorin, 2016, p. 758) as “manufacturing networks are more than just the sum of their sites” (Friedli et al., 2014, p. 26). Following the typology provided by Rudberg & Olhager (2003, p. 35), an IMN is also called “intra-firm network”. It can be distinguished from other constructs by the number of sites per organization and the number of organizations within the network (figure 3).

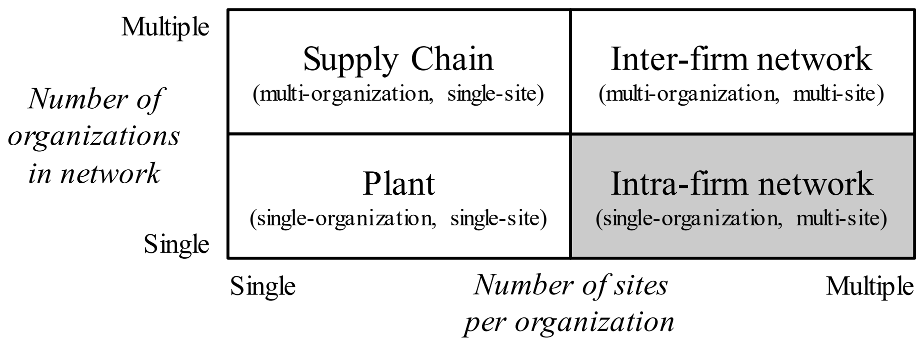


Figure 3: Different types of networks (Rudberg & Olhager, 2003, p. 35)

IMNs can be delayered into two decision layers: configuration and coordination (Cheng, Chaudhuri, & Farooq, 2016; Cheng et al., 2015; Colotla et al., 2003; Friedli et al., 2014).

[2] *IMNs differ from global production networks (GPN), which are discussed by social scientists and economic geographers. GPNs are defined as “a conceptual framework that is capable of grasping the global, regional, and local economic and social dimensions of the processes involved in many (though by no means all) forms of economic globalization” (Cheng et al., 2014, p. 172). The following research will focus on IMNs.*

This understanding can be traced back to Porter (1986, p. 17), who proposed that companies that operate several geographically dispersed sites can derive a competitive advantage from coordination and configuration factors. With reference to Colotla et al. (2003, p. 1189), configuration can be seen as the structure of an IMN, while coordination is an infrastructural element that is related to the relationship between the sites. Hayes et al. (2005, p. 139) point out that coordination and configuration are both central factors for designing an IMN. Although network configuration and coordination are closely linked, the integration of both aspects is relatively limited in literature (Pontrandolfo & Okogbaa, 1999; Shi & Gregory, 1998). The two decision layers must, with reference to Friedli et al. (2014, p. 45), fit to the global manufacturing strategy.

2.3.2 Configuration

Network configuration covers strategic decisions regarding the design, size and structure of an IMN. This includes particularly network and site specialization decisions. By definition, such networks are in flux and very dynamic from a geographical and organizational perspective (Coe, Dicken, & Hess, 2008, p. 272). However, changes at one single site are affecting other facilities in the entire manufacturing network. So most decisions on site level should be perceived as network decisions and from this point of view a separation of both topics is not possible (Cheng et al., 2015, p. 1312; De Toni & Parussini, 2010, p. 3; Feldmann et al., 2013, p. 5708). One can assume, for example, that the equipment of sites, production capacities, utilization of process technologies or the degree of automation are central measures to set up sites and align it to a specific plant role within an IMN. Internal supply chain and resources are also configurational criteria (Friedli et al., 2014, p. 46).

The starting point of a network configuration consideration are typologies of (existing) geographically dispersed plants. For instance, Vos (1991, p. 128,129) summarized the “choice of a new production location”, “relocation of production” and “reallocation of production” as the three main types of decisions which are related to network configuration. These decisions clarify the competences and specialization of each site. Consequently, it comprises site specialization aspects such as plant age (history), characteristics, location, number, or roles of sites. In this context, companies have to define how many sites they want or need to operate and where they should be located (De Meyer & Vereecke, 1994, p. 5; Demeter & Szász, 2016, p. 188; Porter, 1986, p. 20). For example, operating a few large plants may expose economies of scale or cause less coordination effort. In contrast, several small sites are usually more difficult to manage, but reduce risks due to diversification, are quicker in adapting new technologies, and are more flexible regarding dynamic customer demands (Hayes et al., 2005, p. 142; Jacob & Strube, 2008, p. 26). In addition, the ownership of facilities, resource allocation to different plants and relationships are aspects to be considered (De Toni & Parussini, 2010, p. 4).

Ferdows (1989, 1997b) was the first who presented a concept for strategic manufacturing site specialization and roles within an IMN. In the following years, several authors introduced additional concepts to explain site specialization in IMNs. As site roles as well as plant location decisions are key factors that shape a manufacturing network (Szwejczewski et al., 2016), both aspects are key aspects of the systematic literature review (chapter 2.5).

Apart from site specialization, Hayes & Schmenner (1978) were one of the first to study strategies of facilities within an IMN by introducing the concept of *product-* and *process-oriented* organizations. Their assumption is that a *process-focused* network is more challenging to coordinate compared to a *product-oriented* strategy. Their research confirmed that proposition as a *process-focused* network consists of plants that must coordinate both up-stream as well as down-stream operations (Feldmann & Olhager, 2013, p. 724; Hayes & Schmenner, 1978, p. 112). Furthermore, Kulkarni, Magazine, & Raturi (2004, p. 189) found that although the economies of scale are lower, companies may favor the *process-focused* network as it offers significant risk-pooling benefits. Schmenner (1982) extended the findings of Hayes & Schmenner (1978) as he added *market area* and *general purpose* strategy (Schmenner, 1982, p. 77,78):

- *Product-oriented:* A product-oriented strategy focuses on a single or a few products. Hence, each site has definite allocated products, which is most reasonable when the company’s output is very different (e.g. geometrically, material, complexity).
- *Market area*: Following this strategy, each plant is responsible for a single area or region. Industries such as furniture, wood, chemical, or beverage very often apply this strategy as their products have either high transportation costs (including tariffs), local variants, or are of low added-value.
- *Process-oriented*: In such a network all products manufactured by a specific technology or process are partly produced in one plant. After processing, the product is typically transferred to another (assembly) plant. This strategy is particularly suitable for producing complex products and unlocking economies of scales.
- *General purpose*: Flexibility is the main reason for this strategy. These networks are flexible and adjustable as they can be assigned to any market, product or

process. This strategy is most common for products with a short life cycle and uncertain demand.

Likewise, Hayes et al. (2005, p. 145) suggest a pattern of types to describe network configuration, which are closely related to Schmenner (1982). *Vertical networks* are comparable with process-focused networks, *horizontal network* to product-focused networks, *mixed networks* are similar to general purpose strategy, and *orchestrated networks* describe collaborative setups including supplier base.

Another approach to discussing the configuration of IMNs is Shi & Gregory's (1998, p. 211) map, which groups seven possible configurations into four blocks: *regional focused networks, multi-domestic autonomy networks, global exporting networks,* and *global coordination networks*. The dimensions of this framework are, on the one hand, geographical dispersion of manufacturing operations and, on the other hand, coordination between the manufacturing operations. The different combinations show the relationship between the characteristics of the networks and transformation. This map is complemented with examples from other scholars like Flaherty (1986) or Maruca (1994).

Moreover, Bartlett & Ghoshal (1989) propose three types of companies which are positioned between national differentiation and global coordination. First, *global* orientation results in low pressure for national differentiation and high pressure for global coordination. *Multi-domestic* companies have to high pressure for national differentiation and low pressure for global coordination, whereas *transnational* orientation involves high pressure for national differentiation and high pressure for global coordination. This typology was successfully tested by Harzing (2000, p. 115), who collected data from 166 subsidiaries of 37 international companies. Thus, companies with more or less similar customer needs are operating a *global* strategy. If they possess a high local responsiveness, it arises from local marketing activities. In contrast, *multi-domestic* companies offer products and services, which are highly differentiated to meet local customer demands. These local demands are affected by cultural, political or social differences. Finally, *transnational* companies combine characteristics of *multi-domestic* and *global* companies. Harzing (2000) and Bartlett & Ghoshal (1989) suggest that depending on the environmental factors, a company should select the type that fits to the dynamic environment.

In practice, companies usually apply a mixture of different approaches and strategies to differentiate their network specialization. Hayes & Wheelwright (1984) point out that such a network specialization is highly dependent on the site specialization.

2.3.3 Coordination

Apart from network configuration, network coordination covers the management and organization of geographically distributed plants in an IMN. Decisions regarding the degree of centralization and standardization, policies (e.g. organizational design), incentives, and exchange mechanisms are elements of network coordination (Cheng et al., 2015, p. 405; Friedli et al., 2014, p. 47; Hayes et al., 2005, p. 125; Khurana & Talbot, 1999, p. 6).

The degrees of centralization and standardization are key subjects of coordination discussions to define decision-making authority and site autonomy (Maritan, Brush, & Karnani, 2004; Meijboom & Vos, 1997). In the following, "autonomy is defined as the extent of freedom of a subsidiary manager to make decisions at the strategic and operational level" (Golini, Deflorin, & Scherrer, 2016, p. 1742). Feldmann & Olhager (2011, p. 7) identified three levels for decision-making processes: *Centralized, decentralized* or *integrated*. *Centralized* decision-making implies that all responsibility and decisions are aligned to the network level. On the contrary, the term *decentralized*, however, describes local autonomy and *integrated* means that both approaches are combined. Thus, decisions are either made by the local sites or centrally (e.g. headquarter). These decisions are related to the following decision categories: process choice, manufacturing technology, capacity levels, relative demand, timing of capacity acquisition, plant focus, plant specialization, make-or-buy decisions, control principles, supplier selection, choice of organizational design, employee competence development, selection of quality tools, selection of improvement programs, short-term and long-term planning (Feldmann & Olhager, 2011, p. 7). Vereecke, Van Dierdonck, & De Meyer (2006) and Maritan et al. (2004) mentioned similar categories. Friedli et al. (2014, p. 117) structured these elements into *systems*, *decisions* and *processes* as basic groups. By combining several literature findings, they extended the list to 24 sub-categories.

Literature on network coordination indicates that resource sharing is another central issue. Galbraith (1990) and Flaherty (1996) see production technology and knowledge as the most important resources, which need to be efficiently coordinated. Ferdows (2003) stresses that companies that can better coordinate the activities and logistics between plants tend to have a superior performance. Typically, there are four types of resources that can be shared between plants (Bartlett & Ghoshal, 1987, p. 49; Vereecke et al., 2006, p. 1738). First, physical goods pool all raw materials, technologies, components, (semi-) finished products, and equipment that need to be transferred within an IMN. Second, information and knowledge can be exchanged. Both are central aspects for the success of an IMN due to the varying access to knowledge as well as the uneven productivity across plants. Thus, an exchange of knowledge and information is necessary to share learnings, process improvements or best-practices (Chew, Bresnahan, & Clark, 1990, p. 158; A. De Meyer & Vereecke, 1994, p. 13; Hayes et al., 2005, p. 125). However, three important preconditions which promote knowledge exchange between factories should be taken into account: capability to transfer know-how, motivation to share know-how and identification of opportunities for know-how exchange (A. De Meyer & Vereecke, 1994). Human resources are the third possible exchangeable factor. This mostly involves experts for developing (e.g. R&D), production or supporting functions (e.g. service, IT). The last group are financial resources. For any kind of exchanged resource, an important consideration is the type of chargeback for receiving a resource.

Other topics, such as incentive systems are also part of network coordination. Incentive systems provide mechanisms to reward and motivate an intended behavior and prevent undesired actions (Holmstrom & Milgrom, 1994, p. 972). From a network perspective, such incentives are fundamental to steering sites and plant managers (Chew et al., 1990, p. 152; Luo, 2005, p. 86). It facilitates the control of individual site performance, rewards sales developments, encourages knowledge sharing and impacts the contribution of overall learning and qualification.

Referring to Bartlett & Ghoshal (1987, p. 49), coordination costs are usually high due to financial and human resources effort. Although the internet has been a powerful tool to enable geographically dispersed plants to exchange information, the standardization and application of information exchange flow is still resource-intensive (Hayes et al., 2005, p. 125). Moreover, network coordination and configuration need to be integrated as many aspects such as site roles or knowledge transfer are intricately connected (De Toni & Parussini, 2010, p. 8; Rudberg & Olhager, 2003, p. 38). Meijboom & Vos (1997, p. 803) add that a "configuration decision, in turn, leads to a certain form of coordination". This fact becomes clear in the empirical part of this research (chapter 4 and 5).

2.4 Systematic literature review

Identifying, formulating and clarifying the research topic is always the starting point of a research project (Ghauri & Grønhaug, 2005, p. 29; Saunders et al., 2009, p. 21). Hence, a literature review is the "essential first step" of research (Baker, 2000, p. 219) and builds on the existing knowledge in a specific field (Webster & Watson, 2002, p. 48,49). Such a literature review aims at understanding the background and dependencies of the addressed phenomena and should identify research focus and gaps to derive RQs (Punch, 2005, p. 33; Rowley & Stack, 2004, p. 32). First, this avoids the reinvention of existing solutions (vom Brocke et al., 2009, p. 2) and, second, it ensures rigor by making use of the existing knowledge base (Hevner et al., 2004, p. 88). Therefore, a critical literature review is crucial for scholars to understand the content and limitations of a research field (Cooper, 1988, p. 104; Gill & Johnson, 2002, p. 25; Jankowicz, 2005, p. 161; Webster & Watson, 2002, p. 13). However, especially for emerging research fields such as digitalization, the literature review can become remarkably complex (vom Brocke et al., 2009, 2015).

In the context of operations management, four main literature streams have been analyzed: *manufacturing strategy*, *multinational companies*, *international manufacturing networks*, and the knowledge base regarding *production technology and processes (including digitalization)*.

In general, a variety of approaches for conducting a systematic literature review exist (e.g. Cooper, 1988; Hochrein, Glock, Bogaschewsky, & Heider, 2015; Levy & Ellis, 2006; Torraco, 2005; vom Brocke et al., 2009; Webster & Watson, 2002). The author is convinced that the three-step approach of Levy & Ellis (2006) fits best for this research:

a. Literature *input* (searching, collecting)
b. Literature *processing* (analyzing, synthesizing)
c. Literature *output* (writing)

The initial literature search was conducted in July 2017 and revised in March 2018.

2.4.1 Literature input

The literature *input* includes selection of databases and journals as well as search approaches. As a first step, leading operations management journals were identified and screened to find major contributions and obtain a broad overview of the research topic (Torraco, 2005, p. 359; Webster & Watson, 2002, p. 16). Accordingly, databases and journals in the context of this research were recognized and classified (Herz, Hamel, Uebernickel, & Brenner, 2010, p. 4). Prasad & Babbar (2000), De Toni & Parussini (2010), Petersen, Aase, & Heiser (2011), and Cheng et al. (2015) all suggested ways of covering literature on manufacturing strategy, multinational companies and IMNs. In addition, the journal set is extended by considering the VHB journal ranking on “production” as well as “technologies, innovation, and entrepreneurship” (TIE) journals to address the topics of technology and digitalization (Hennig-Thurau & Sattler, 2015). From this cumulated list the author eliminated journals with a distinct focus (e.g. Journal of Service Management, International Journal of Entrepreneurship and Innovation, Mathematics of Operations Research, Logistics Research). The final list is presented in in appendix A. Journals were obtained from the databases *EBSCOhost, Emerald, ProQuest (ABI/INFORM),* and

ScienceDirect. The applied parameters are presented in appendix B. In general, the literature review focuses on scientific, peer-reviewed journals and renowned conference proceedings. Although it is generally accepted that the quality of conference proceedings is lower compared to journals (Levy & Ellis, 2006, p. 187; Webster & Watson, 2002, p. 16), conference papers are also included in the literature review to consider "more recent ideas and new technologies" (i.e. digitalization) (vom Brocke et al., 2015, p. 210). This is because, so far, scholarly journals have rarely mentioned digitalization. Ferdows (2018, p. 399) adds that in some aspects related to digitalization, practice and industrial companies are ahead compared to academia. In fact, the author did not exclusively focus on the journal list presented in appendix A, but considered all literature input that seemed to be relevant for the respective fields of research.

According to Tranfield, Denyer, & Smart (2003, p. 215), transparency of the review process is enhanced by adding the choice of keywords and timelines. The selection of keywords is crucial, since it sets "the parameters of the research itself" (Baker, 2000, p. 222). Therefore, precise keywords and search strings have been applied and clustered into five groups (appendix C). The keywords were carefully extracted from known literature and complemented with synonyms to enhance search results.

2.4.2 Literature processing

The second step, literature *processing*, includes the application, analysis, synthesis, and evaluation of literature. Hence, the author summarized, linked, interpreted, and evaluated the reviewed literature. Appendix D shows the results of the systematic literature review. It provides the clusters, databases, the total number of articles found as well as the number of articles considered as relevant (in brackets).

Except for duplications, in total 77 articles were identified as relevant for this thesis. Nevertheless, only manufacturing networks are occasionally discussed in context with technology, but as mentioned beforehand, mostly with technology as a fixed constraint. It is obvious that literature on the specific topics plant roles and locations does not sufficiently discuss this in combination with digitalization and technology. This outlines the missing link between plant roles and digitalization in scientific literature. Further, the keyword search is seen as an initial step of literature screening and was complemented by forward and backward searches to further enhance the knowledge base (Levy & Ellis, 2006, p. 190,191). Forward search reviews literature which have cited an article or author, whereas backward search refers to reviewing the references of a specific article (Webster & Watson, 2002, p. 16). The purpose of the forward and backward search was to detect additional publications that were not captured by the keyword search (vom Brocke et al., 2015, p. 216).

2.4.3 Literature output

Literature *output*, the final step, comprises all steps of writing an academic literature review. By applying keyword, forward and backward search, the author has gathered an extensive knowledge base in the relevant research streams. The literature streams on plant roles, locations, technology, and digitalization are discussed separately in chapters 2.5 and 2.6, because scientific literature tends to do the same.

2.5 Analysis of the knowledge base on plant roles and locations

This chapter introduces site specialization as part of IMN configuration. Two main literature streams are pertinent: plant roles and location decisions (advantages). First, location decision criteria will be presented and then different plant roles and integrated site perspectives from literature will be discussed. The literature review will show the need for a structured research on site roles and the impact of technologies (cf. Ferdows, 2018).

2.5.1 Factory location decisions

Location choices span all decisions concerning the geographical positioning of plants or other organizational entities. From the perspective of a single plant, location is defined as a structural element, but from a multi-plant perspective it becomes a configurational element (Hayes & Wheelwright, 1984). As such it is part of the strategic management of IMN configurations (L. Chen et al., 2014, p. 154). The literature on location decisions can be classified into mathematical approaches and factor assessment. While mathematical approaches mainly concentrate on cost reduction and profit maximization (e.g. T. Drezner & Drezner, 2016; Z. Drezner & Hamacher, 2004; Melo, Nickel, & Saldanha-da-Gama, 2009), factor assessments are based on strategic concerns in decision-making. Especially, the access to numerous "immobile natural endowments" (Dunning, 1988, p. 30) such as advantageous labor costs or state-of-the-art infrastructure are objects of study in this field. A variety of drivers for location decisions and advantage have been identified. Whereas at the beginning most researchers focused on Ferdows' (1989, 1997b) classification of primary site reasons (*proximity to market, access to low-cost production* as well as *access to skills and knowledge*), the list got extended. Other popular factors are for instance access to low-cost energy, proximity to suppliers, local technology, freight rates, infrastructure, complementary services, overcoming tariff and non-tariff barriers, or taking advantage of currency fluctuations (cf. E. Abele, Meyer, Näher, Strube, & Sykes, 2008; Badri, Davis,

& Davis, 1995; Brush, Marutan, & Karnani, 1999; Buckley & Casson, 1998; L. Chen et al., 2014; A. De Meyer & Vereecke, 1994; Dubois, Toyne, & Oliff, 1993; Dunning, 1988; Ellram, Tate, & Petersen, 2013; Flaherty, 1986, 1996; Hamel & Prahalad, 1985; Meijboom & Vos, 1997; Rugman & Verbeke, 2001; Shi & Gregory, 1998; Spring et al., 2017; Vereecke & Van Dierdonck, 2002; Yip, 1992). Hence, "location decisions must be understood not just through the lens of economic attractiveness of one region or country over another, but also as a decision where many organizational and technological interdependencies become relevant" (Ketokivi et al., 2017, p. 20). Reuter, Prote, & Stöwer (2016) add the aspects of influenceable (e.g. size, technological equipment) and uninfluenceable site characteristics (e.g. tariff regulations).

Ranking location decision factors is not easy as the importance of criteria varies either from company to company or from site to site. Nonetheless, for the majority of companies "the most important determinants tend to be those that reflect how firms manage their multiple plant networks such as proximity to important customers and suppliers" (Brush et al., 1999, p. 127). Therefore, legal, economic and political factors tend to be dominating factors regarding location decisions (Prasad & Babbar, 2000, p. 222). Ellram et al. (2013, p. 20) add that supply chain-related factors such as transportation cost, risk of supply interruption, etc. are becoming more essential in manufacturing location decisions. In recent years, scholars have concentrated on additional aspects. In consequence, apart from the economic dimension, environmental and social factors have increased in importance for location decisions (Brennan et al., 2015; L. Chen et al., 2014; Golini, Longoni, & Cagliano, 2014; Theyel, 2012). For example, environmental factors such as earthquakes, thunderstorms, or electric/water scarcity can halter manufacturing activities for days or even months (Economy & Lieberthal, 2007). Therefore, the three dimensions can be summarized as the "triple-bottom-line" and the combination results in "sustainable location decisions" (L. Chen et al., 2014, p. 161).

However, besides qualitative decision criteria, calculable costs are very important (Gray, Esenduran, Rungtusanatham, & Skowronski, 2017, p. 38). Although it is difficult to determine cost and other factors in a dynamic environment, a short-term and long-term cost-utility analysis must always be one of the evaluation stages (Kinkel, 2009, p. 15). Hence, a total, integrated cost and return-on-investment (ROI) analysis is advisable (T. Meyer, 2008, p. 111; Tombak, 1995, p. 434).

Table 4 provides an overview of the main factory location criteria. The categories stem from Colotla (2003) and are an extension of Vereecke & Van Dierdonck's (2002, p. 513) original classification. Besides, the author added further criteria and factors to the list.

Table 4: Overview location decision criteria (adapted from Colotla (2003) and extended by the author)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Favorable factors of production										
Availability and/or low-cost of labor	●	●	●	●	●	●	●	●	●	●
Materials, components and raw materials	●	●	●	●	●	●	●	●	●	●
Access to low cost energy or capital	●	●		●	●	●			●	
Low property costs				●	●	●			●	●
Local infrastructure (roads, electricity, airports, etc.)		●		●	●	●	●			●
Favorable economic, social and political factors										
Government/regional incentives		●	●	●	●	●	●	●		
Local taxation		●	●	●	●	●	●	●	●	●
Stability of exchange rates							●	●	●	●
Favorable social climate (high productivity, low absenteeism rate, etc.)		●	●		●		●	●	●	●
Civil liberties, human rights, equity, property rights protection, and safety									●	●
Language and culture				●		●				●
Duties, tariffs or trade-quotas, customs		●	●	●	●	●	●		●	●
Country of origin effect (e.g. "made in X")							●			
Proximity to (current) customers and/or suppliers										
To benefit from rapid/reliable delivery		●	●		●	●	●	●	●	●
To benefit from low logistics costs/low inventories		●	●	●	●		●	●	●	●
To facilitate collaboration (product design, technical support, etc.)		●	●	●	●	●		●		●
Access to skills and knowledge										
Highly skilled employees		●	●	●	●	●	●	●	●	●
Technological centers/resources (universities)		●	●	●	●		●		●	●
Local market intelligence						●				
Access to strategic targets										
Strategic (potential) customers/market access		●	●	●			●	●	●	●
Pre-empting the competition/defending market	●	●					●	●		
Proximity to competitors		●					●	●	●	
Economies of scale and scope										
Integration/centralization of production (scale)			●		●	●	●			
Global sourcing			●				●			
Use of in-house developed processes globally	●		●							
Sharing of activities or overheads across plants			●			●	●			
Operating Flexibility										
Ability to produce from various locations (risk)			●			●	●			●
Global planning and capacity management			●			●	●			
Capacity allocation from exchange rate fluctuations			●				●			
Exchange rate hedging and/or tax minimization		●	●				●			
Product, process or personnel mobility across plants						●				
Cross-subsidizing markets (strategically)							●			●
Internal learning and sharing of best practices			●		●	●	●			●
Others		●	●			●		●	●	
Environmental factors										
Environmental regulations		●			●			●	●	●
Ecosystem vitality (bio diversity protection, etc.)								●	●	●
Environmental health (air pollution, water quality, burden of disease, etc.)		●							●	●
Environmental factors within production (recycling, renewable resources, waste treatment, etc.)								●	●	●

(1) (Ferdows, 1997b); (2) (Vereecke and Van Dierdonck, 2002); (3) (Flaherty, 1986; 1996); (4) (Dunning, 1998); (5) (De Meyer and Vereecke, 1994); (6) (Shi and Gregory, 1998); (7) (Yip, 1992); (8) (Ellram, 2013); (9) (Chen et al., 2014); (10) (Gray et al., 2017)

An evaluation of locations and sites is a step by step process, from a rough to a detailed plan (Friedli et al., 2014, p. 27). Thereby, it is crucial that the required location criteria are selected to derive the most suitable location. In doing so, typically three levels of uncertainty occur (Buhmann & Schön, 2009, p. 280):

- *Uncertainty 1*: There is uncertainty which location factors are crucial for location decisions and what is the possible effect on site's performance of a company.
- *Uncertainty 2*: It is indeterminate how the national and regional exogenous factors will develop in the future (e.g. labor costs, exchange rates).
- *Uncertainty 3*: There is uncertainty about the expected extend of performance that can be realized at a location (e.g. sales volumes, product quality).

Ketokivi et al. (2017) summarize the four main implications related to location decisions. First, location decisions are guided by locational factors, e.g. *access to labor, knowledge* or *proximity to markets*. Second, locations are highly influenced by organizational factors such as plant roles and inter-functional interdependencies. Accordingly, the essential question is how to organize all geographically distributed manufacturing plants. Third, decisions about geographically distributed activities are based on temporal considerations. Factors and arguments can change over time due to dynamics of economies and governmental trade policies, which affect a regions' attractiveness (Ellram et al., 2013, p. 19; Meijboom & Vos, 1997, p. 804). Fourth, many decisions are based on beliefs rather than facts (Simon, 1997, p. 69). Thus, location decisions are a dynamic construct, which need reevaluation on a regular basis (Kinkel, 2009, p. 8).

2.5.2 Strategic plant roles and site responsibilities

Plant roles have their roots in the classification of *manufacturing sites in international operations management* as well as in the organization of *subsidiaries in the international strategy* literature stream. The theory on strategic plant roles can be backdated to Skinner's (1974) focused factory concept. Skinner (1974, p. 114) stated that "a factory that focuses on a narrow product mix for a particular market niche will outperform the conventional plant, which attempts a broader mission. Because its equipment, supporting systems, and procedures can concentrate on a limited task for one set of customers, its costs and especially its overhead are likely to be lower than those of the conventional plant. But, more important, such a plant can become a competitive weapon because its entire apparatus is focused to accomplish the particular manufacturing task demanded by the company's overall strategy and marketing objective". In other words, a focused factory concentrates on one strategic activity or specific task as a plant cannot fulfil several tasks at a high level of efficiency.

In recent years, many role typologies have been developed. Table 5 provides an overview of 62 plant and subsidiary roles from literature. While plant roles are rooted in the manufacturing network management, subsidiary roles belong to strategy management. Plants are seen as “fundamental building blocks of manufacturing networks” (Christodoulou et al., 2007, p. 5) and therefore have a long history in research. Subsidiaries are defined as “any operational unit controlled by the MNC [multinational corporation] and situated outside the home country” (J. Birkinshaw, Hood, & Jonsson, 1998, p. 224). Many researchers have developed various typologies for plant and subsidiary roles to classify manufacturing sites and allocate responsibilities. However, a strict differentiation of plant and subsidiary roles is not possible as both terms are interlinked. In the following, the terms plant and subsidiary roles will be used interchangeably. Some of these typologies will be briefly presented.

The review is based on Daniel (2010), Kretschmer (2008), Schmid & Kutschker (2003), Tykal (2009), and was augmented by the author. It points out the applied methods and focus areas of the specific plant role as well as its origin. The focus categories – location competences, knowledge flow, product scope, and level of autonomy or integration – stem from Enright & Subramanian (2007), Cheng et al. (2011) and Mediavilla et al. (2014). Even though there is a wide variety of publications dealing with plant roles, Ferdows (2018, p. 393) emphasizes that more research in this field is needed. Interestingly, most roles are based on only a few main typologies or their specific dimensions. For instance, 17 plant role typologies are based on Ferdows (1989, 1997b), 12 on White & Poynter (1984) and nine on Bartlett & Ghoshal (1986).

Starting point for the role typologies of White & Poynter (1984) as well as later for D’Cruz (1986) was the company’s strategy and globalization pressure. They defined which plant roles are most suitable depending on the intensity of global competition. Similarly, the plant roles of Porter (1986), Prahalad & Doz (1987) as well as Bartlett & Ghoshal (1986) are directly related to strategy. These authors, however, rather see the tension between the degree of integration and the degree of local responsibility as the basis for a role definition. For instance, Bartlett & Ghoshal (1986) derived a matrix with the dimensions strategic importance of the local environment and competence of the subsidiary. Marcati (1989), Jarillo & Martinez (1990), Roth & Morrison (1992), Hoffman (1994), and Taggart (1997b) among others also chose a similar classification to describe plant roles.

Table 5: Overview plant and subsidiary role typologies (own illustration)

Author	**Year**	**Method**	**Location**	**Competences**	**Knowledge flow**	**Product scope**	**Level of autonomy or integration**	**Conceptual framework or model mainly based on**
Bartlett & Ghoshal	1986	Q-LS	●	●				-
Beechler, Bird, & Taylor	1998	Q-LS			●			-
Benito, Grøgaard, & Narula	2003	Q-LS		●		●		*Bartlett & Ghoshal (1986); White & Poynter (1984)*
Birkinshaw & Morrison	1995	Q-LS	●	●		●	●	*Bartlett & Ghoshal (1986); Jarillo & Martinez (1990); White & Poynter (1984)*
Blomqvist & Turkulainen	2011	CS	●	●				*Ferdows (1989, 1997b); Johansen & Riis (2005); Riis et al. (2007)*
Cheng et al.	2011	CS	●		●	●	●	*Ferdows (1989, 1997b); Vereecke et al. (2006)*
Chiesa	1996	CS		●	●			*a)*
D'Cruz	1986	CS	●				●	*White & Poynter (1984)*
Daub	2009	CS		●			●	*b)*
Delany	2000	I		●		●		*White & Poynter (1984)*
Demeter & Szász	2014	Q-LS	●	●				-
Demeter & Szász	2016	Q-LS	●	●			●	*Ferdows (1989, 1997b); Feldmann et al. (2013)*
Doz & Prahalad	1984	CS	●				●	-
Enright & Subramanian	2007	-	●	●		●	●	*Bartlett & Ghoshal (1986); White & Poynter (1984)*
Feldmann & Olhager	2009	Q-LS	●	●				*Ferdows (1989, 1997b)*
Feldmann et al.	2013	Q-LS		●				*Ferdows (1989, 1997b)*
Ferdows	1989, 1997b	CS	●	●			●	-
Forsgren & Pedersen	1998	Q-LS					●	-
Fusco & Spring	2003	CS	●	●				*Ferdows (1989, 1997b)*
Golini et al.	2014	Q-LS		●				*Ferdows (1989, 1997b)*

Author	Year	Method	Location	Competences	Knowledge flow	Product scope	Level of autonomy or integration	Conceptual framework or model mainly based on
Gupta & Govindarajan	1991, 1994	Q-LS			●			-
Hallavo, Kuula, & Putkiranta	2015	CS	●	●			●	*b); Ferdows (1989, 1997b)*
Harzing & Noorderhaven	2006	Q-LS			●			*Gupta & Govindarajan (1991, 1994)*
Hoffman	1994	CS	●	●				*Bartlett & Ghoshal (1986)*
Hogenbirk & van Kranenburg	2006	Q-LS	●	●			●	*White & Poynter (1984)*
Hood & Young	1987	CS, Q-LS	●				●	*White & Poynter (1984)*
Jarillo & Martinez	1990	CS, Q-SS	●				●	*Bartlett & Ghoshal (1986); White & Poynter (1984)*
Johansen & Riis	2005	CS, Q-LS		●	●		●	-
Jones & Davis	2000	-	●	●				*a)*
King & Sethi	1999	Q-LS	●				●	*Bartlett & Ghoshal (1986)*
Kinkel, Kleine, & Diekmann	2014	I	●	●			●	*Ferdows (1989, 1997b)*
Kim, Rhee, & Oh	2011	CS	●	●			●	*Ferdows (1989, 1997b)*
Kuemmerle	1999	Q-SS	●					*a)*
Marcati	1989	Q-SS					●	*Bartlett & Ghoshal (1986)*
Maritan et al.	2004	Q-SS	●	●				*Ferdows (1989, 1997b)*
Medcof	1997	-	●	●				*a)*
Mediavilla et al.	2014	CS	●	●			●	*Ferdows (1989, 1997b)*
Meijboom & Voordijk	2003	CS	●	●				*Ferdows (1989, 1997b)*
Meijboom & Vos	2004	CS	●	●				*Ferdows (1989, 1997b)*
Miller & Roth	1994	Q-LS	●					*White & Poynter (1984)*
Mudambi	1999	Q-LS	●				●	*D'Cruz (1986)*
Nobel & Birkinshaw	1998	Q-SS	●	●				*a)*

Author	Year	Method	Location	Competences	Knowledge flow	Product scope	Level of autonomy or integration	Conceptual framework or model mainly based on
Papanastassiou	1999	Q-LS	●	●				*White & Poynter (1984)*
Papanastassiou & Pearce	2005	Q-SS		●			●	*a)*
Porter	1986	CS	●	●				-
Prahalad & Doz	1987	CS	●				●	*Doz & Prahalad (1984)*
Randøy & Li	1998	Q-SS		●				*Gupta & Govindarajan (1991, 1994)*
Riis, Johansen, Vejrum Waehrens, & Englyst	2007	I		●	●		●	*Ferdows (1989, 1997b); Johansen & Riis (2005)*
Roth & Morrison	1992	Q-LS		●			●	*Bartlett & Ghoshal (1986)*
Schmid & Daub	2005	Q-SS		●			●	*b)*
Surlemont	1998	-					●	-
Taggart	1997a	Q-LS		●			●	*Jarillo & Martinez (1990)*
Taggart	1997b	Q-LS	●				●	*Bartlett & Ghoshal (1986)*
Taggart	1998	Q-LS		●			●	*Jarillo & Martinez (1990)*
Tavares & Young	2006	Q-LS	●			●	●	*White & Poynter (1984)*
Turkulainen & Blomqvist	2010	Q-LS	●	●		●		*Ferdows (1989, 1997b)*
Vereecke & Van Dierdonck	2002	CS	●	●				*Ferdows (1989, 1997b)*
Vereecke et al.	2006	CS	●	●	●			*Ferdows (1989, 1997b)*
Vokurka & Davis	2004	Q-LS				●	●	-
Wang, Liu, & Li	2009	Q-LS			●		●	*Gupta & Govindarajan (1991, 1994)*
White & Poynter	1984	Q-SS	●	●		●	●	-
Young, Hood, & Dunlop	1988	Q-LS	●			●	●	*White & Poynter (1984)*

Note: In case of unavailable information the lines are left blank   a) Focus on R&D units   b) Focus on service units
I = Interview, CS = Case study, Q-SS = Quantitative small sample (≤50), Q-LS = Quantitative large sample (>50)

In contrast to these rather universal typologies, Gupta & Govindaraian (1991) and Chiesa (1996) differentiated sites according to the form of knowledge in- and outflow. Randøy & Li (1998) developed a comparable approach by classifying the level of resource flow. Furthermore, based on another dimension, Vokurka & Davis (2004) developed a typology, which focuses on ten site factors that are correlated to *processes, products, materials, market,* and *customers*. By analyzing 305 plants, Vokurka & Davis (2004) empirically derived the strategic groups *standardizers, customizers* and *automators*.

Apart from these typologies, one of the most recognized and preferably used plant role types was created by Ferdows (1989, 1997b). Ferdows' intention was to provide suggestions for an ideal design of a manufacturing network as well as deriving an efficient and effective configuration of foreign production sites. Accordingly, "the reasons for establishing a factory abroad determine the way the company should plan, design, construct, and commission that factory. What is the strategic role of the factory that is the starting question" (Ferdows, 1989, p. 5). Ferdows' typology is the first of its kind which concentrates exclusively on manufacturing sites in the field of international strategy research (Cheng et al., 2011; De Toni & Parussini, 2010; Mediavilla et al., 2014; Meijboom & Vos, 2004; Tykal, 2009). Ferdows' (1997b) *lead* factory concept will be discussed in more detail in chapter 3.4.4.

Vereecke et al. (2006) suggest a pattern of plant types for IMNs based on the knowledge flows across plants. The empirically derived typology points out that the types of plants have a different age, focus and strategic role (Vereecke et al., 2006, p. 1737). Moreover, the degree of autonomy, existing resources and amount of investments differ. Their plant roles can be summarized as *isolated plants, receiving plants, hosting network players,* and *active network players*. The *isolated* and *receiving* plants are not actively taking part in the exchange of knowledge within the IMN. Comparing the *receiver* with the *isolated* plant, the *isolated* plant is also separated from innovation and material flow. The *hosting network player* is characterized by an active contribution to the manufacturing network and a high degree of innovation and knowledge flow. Finally, the *active network player* is significantly embedded in the network. The outflow of innovations and people as well as the degree of communication is much higher compared to the *hosting network player*.

In contrast, Demeter & Szász (2016) concentrated on plant characteristics as a function of competences and region. Their study focuses on the differences between Western European and Central/Eastern European countries. For instance, autonomy, embeddedness and global orientation is more typical for Western European plants and plant age is correlated with level of competences as older plants were able to accumulate more knowledge (Demeter & Szász, 2016, p. 202). Another insight is that higher competences are connected to higher responsibility for know-how dissemination.

In recent years, many scholars adapted the existing typologies. For example, Delany (2000), Hogenbirk & van Kranenburg (2006) and Hood & Young (1987) based their plant roles on White & Poynter (1984). Particularly, the dimensions *product-, market-* and *value-added scope* are reused by the authors. Ferdows' (1997b) *lead* factory concept attracted even more attention. This concept has been applied and modified among others by Fusco & Spring (2003), Meijboom & Voordijk (2003), Meijboom & Vos (2004), Cheng et al. (2011), Blomqvist & Turkulainen (2011), and Golini, Longoni, & Cagliano (2014). Some researchers such as Vereecke & Van Dierdonck (2002), Maritan et al. (2004), Vereecke et al. (2006), or Deflorin, Dietl, Lang, & Scherrer-Rathje (2012) also verified and tested the model in the field. For instance, Vereecke & Van Dierdonck (2002) collected data from about 50 plants from companies headquartered in Western Europe. They found that the perception of a strategic role and the real role of a plant usually differ.

As seen in table 5, literature provides a wide range of different typologies of strategic roles in the context of IMNs. The existing plant typologies are useful for categorizing a current state, but do not contribute to the discussions about prescriptive or future configurations (Blomqvist, Turkulainen, Eloranta, & Laiho, 2014, p. 64; Cheng et al., 2015, p. 403). To close this gap, plant roles need to be reconsidered and operationalized (Meijboom & Vos, 2004, p. 129; Turkulainen & Blomqvist, 2011, p. 7) for dealing with digital technologies. Despite the precious insights from other authors, the roles of Ferdows (1997b), White & Poynter (1984) and Bartlett & Ghoshal (1986) are most accepted, frequently adapted by other scholars and will be discussed in more detail in chapter 3.4.

2.5.3 Integration of site and network perspective

Strategic plant roles and location decisions focus on sites and neglect the network perspective. According to Feldmann et al. (2013, p. 5696), "plant roles are an integral part of the network configuration and that when part of the network changes it has implications for the rest of the network, which may need to be realigned". Instead of concentrating on single factories, the whole network as a cluster of single plant roles deserves more attention. Therefore, understanding and discussing plant roles from an overall network perspective seems to be of increasing relevance (Friedli et al., 2014, p. 90). Based on table 25 in appendix E, a few approaches, which combine both site and network perspective, will be introduced.

Colotla et al. (2003) were among the first pointing out the inter-link between site and network level. To explore the interdependencies and relations between both, they derived an approach with the dimensions *factory-level competitive position, network-level competitive position,* and *time*. Following Colotla et al.'s (2003) assumption, site and network are strongly (inter-)dependent regarding similar operational performance categories such as cost, quality, dependability, speed, flexibility, innovation, etc. The improvements on site level (e.g. reduce cost by reducing labor costs) or on network level (e.g. relocation of factories to low-cost areas) are equally beneficial.

In contrast to the framework of Colotla et al. (2003), another approach by Christodoulou et al. (2007) explicitly considers the plant role perspective. As definite roles and responsibilities are central elements, the "mountain model" is an exception in the context of integrating site and network level. The main dimensions are, first, *configuration and layout of the processes* executed at the site, second, *process stage*, third, *primary geographic purpose*, and, last, the *activities performed* by a site. In this case, the configuration and layout describe the organization of production at a site (e.g. shop fabrication, continuous production or degree of automation). The geographic purpose is attributable to Ferdows' (1997b) understanding of strategic site reasons and competences.

Miltenburg (2009) offers a comprehensive framework by combining several approaches, which are rooted in operations management theory. Both site and network perspectives are combined to align the network strategy. On the one hand, Miltenburg (2009) utilizes Ferdows' (1997b) site role model to determine the level of competence of a plant and the strategic reason (*proximity to market, access to knowledge and skills, access to low-cost production*). However, Miltenburg (2009) tries to avoid a more complex approach by reducing the number of possible activities in a factory and the level of capability. In a next step, plant roles are linked to different types of manufacturing networks (*regional, national, multinational, transnational, international, domestic,* and *mixed variants*) and network outputs in the dimensions *accessibility, thriftiness, mobility,* and *learning* (Miltenburg, 2009, p. 6183). Factories having a narrow scope of activities and a low level of capability belong to *server, outpost* or *offshore* factory types. These are typical for less complex manufacturing networks (e.g. *multi-domestic* or *international*). The other three factory types (*source, contributor* and *lead*) are most common in complex manufacturing networks such as *multinational, global* or *transnational*. Last, structural and infrastructural levers are integrated in Miltenburg's (2009) framework, which are related to manufacturing strategy (see chapter 2.2).

Asmussen, Pedersen, & Dhanaraj (2009) describe an IMN as the aggregation of local diamonds based on the work of Porter (1990). Each diamond consists of local competitive rivalry, demand and factor conditions as well as related and supporting industries. The whole network can benefit from either market, technical or supply competences and the strengths of each local diamond.

Feldmann et al. (2013) concentrate on the inter-link between the network perspective and sites roles. It is the first attempt to analyze the effects of plant changes in the context of IMNs. The invented model maps the relationships between *markets, plants* and *level of technical activities*. The last dimension comprises nine elements – starting from pure production as the lowest competence to introduction of new technologies as the highest level of technical activities.

Moreover, Cheng et al. (2011, p. 1312) suggest integrating the site and network perspective, because "whenever part of a network changes, it is unlikely to happen in isolation; instead, it has implications for the entire network". Thus, changes on site level are responsible for entire network modifications. In order to derive an integrated model, they took Shi & Gregory's (1998, p. 211) "map of international manufacturing network configurations" and complemented it with Ferdows' (1997b) plant roles and the modified roles by Vereecke et al. (2006).

In addition, Scherrer-Rathje et al. (2014) introduced a framework based on mathematical equations. Even though it is just a recombination of the dimensions of Ferdows (1997b) and Vereecke et al. (2006), it offers some interesting insights and, even more importantly, it incorporates the site and network level at the same time. The matrix highlights a *competence triangle*, *embeddedness triangle*, *transceiver degree*, and *location advantage*. Scherrer-Rathje et al. (2014) were able to identify a pattern to cluster the sites from their single case study. The first cluster is called *lighthouse site*. Such a site has both a large *embeddedness triangle* as well as a large *competences triangle*. *Support sites* offer low-cost production and serve as extended workbenches. Most of the sites belong to the third cluster, *market producers*. These sites have a high proximity to a market and their level of competences is average (Scherrer-Rathje et al., 2014, p. 25). However, it is more a management tool to visualize the current site's contributions than an instruction on how to proceed and improve factories and the entire network.

Thomas et al. (2015) designed a multifaceted portfolio to outline each site's contribution to the network. By combining network dimensions (i.e. network targets) and site dimensions (i.e. site capabilities and characteristics), the researchers derived an integrated framework to combine network and site perspective.

It can be concluded that site and network level of manufacturing networks are strongly inter-linked. Hence, for deriving and understanding the full potential of a manufacturing network, the consideration and alignment of both perspectives is required. So far, only a few researchers have introduced combined approaches, which consider the relation of sites and network. The majority sees factories as a black box and no approach addresses the question how a site and IMN evolve in the context of technological advancement.

2.6 Analysis of the knowledge base on technology and digitalization

2.6.1 Technology

2.6.1.1 Definition and developments

Manufacturing companies are best described as a "sequence of modular core technologies or technological bundles" (Galbraith, 1990, p. 57). The sites and configuration of a manufacturing company are considerably influenced by the utilization of technologies and assigned products (Nyhuis et al., 2010, p. 231). The ability to develop, select, apply, and exploit new technologies is a central element of the competitive position (Gaimon, 2008, p. 2; Porter, 1985b, p. 60; Santos, Araújo, & Correia, 2015, p. 180; Shen, Chang, Lin, & Yu, 2010, p. 151; Slack & Lewis, 2002, p. 244). Surprisingly, many scholars "seem to assume that this concept is self-explanatory" (Gillespie & Mileti, 1977, p. 8). As a consequence, most researchers use the term technology without any specification. Thus, the term is not consistent in literature (Orlikowski, 1992, p. 399). Table 6 provides an impression of a few scientific definitions[3].

Table 6: Selected definitions of the term technology (own illustration)

Galbrait (1967, p. 12)	*Technology is "the systematic application of scientific or other organized knowledge to practical tasks."*
Gillespie & Mileti (1977, p. 8)	*Technologies are "the types and patterns of activity, equipment and material, and knowledge or experience to perform tasks."*
Bell & Pavitt (1993, p. 163)	*"Technological capabilities consist of the resources needed to generate and manage technical change, including skills, knowledge and experience, and institutional structures and linkages."*
Binder & Kantowsky (1996, p. 91)	*Technology comprises knowledge, skills, abilities and capabilities in solving technical problems, as well as facilities, methods and procedures to implement the scientific knowledge in practice.*

[3] *German linguistic differs between technic and technology. While technology is the knowledge of scientific and technical relations that is used in solving practical problems, technic refers to the concrete application in products or production processes (Specht, Beckmann, & Amelingmeyer, 2002, p. 13). In contrast, the English term technique is more used as a method or procedure.*

Freeman & Soete (1997, p. 24)	*"Strictly speaking, technology is simply a body of knowledge about techniques, as the word itself implies. But it is frequently used to encompass both the knowledge itself and the tangible embodiment of that knowledge in an operating system using physical production equipment."*
Brooks, Weatherston, & Wilkinson (2004, p. 149)	*"Technology is the application of knowledge into some practical form, typically applied to industrial and commercial use."*
Gaimon (2008, p. 1)	*"Technology is the embodiment and deployment of technical and scientific knowledge and discoveries that lead to the creation of goods and services."*
Betz (2011, p. 13)	*"Technology is knowledge of the manipulation of nature for human purposes."*

Besides the more general definitions of technology, Slack & Lewis (2002) propose two concrete definitions of technologies for manufacturing companies:

- "Direct process technology is the appliance of science to those processes which directly contribute to the production and delivery of products and services" (Slack & Lewis, 2002, p. 247).
- "Indirect (or supporting) process technology is the appliance of science to the processes which provide or support the infrastructure for those processes which directly contribute to the production and delivery of products and services" (Slack & Lewis, 2002, p. 248).

In other words, direct process technology affects input factors (e.g. material, products, information) to transform them and produces output factors such as goods or services (Knoben & Oerlemans, 2006, p. 77). Indirect process technologies manage information (e.g. ICT, knowledge exchange) and support the production process or infrastructure. ICT is often regarded as a "game changer" in manufacturing industries and unlocks further benefits (e.g. Haverkort & Zimmermann, 2017; Motwani, Mirchandani, Madan, & Gunasekaran, 2002).

Every company operates a large number of technologies with each of them more or less impacting processes, strategies or products (Porter, 1985b, p. 61). Conversely, "the future is uncertain and most often unpredictable. Technological developments are part of that uncertainty" (Jiang, Kleer, & Piller, 2017, p. 85). With the help of a technology strategy, the development and utilization of technologies can be managed systematically.

2.6.1.2 Technology strategy

Technology strategy is a central aspect of investigation in the context of technologies as it defines the technological objectives and shows the path to target fulfilment. This strategy describes how a company should use technologies to achieve competitive advantage (Schulte-Gehrmann, Klappert, Schuh, & Hoppe, 2011, p. 56). It includes a pattern of decisions in the manner of technology intelligence, timing of introduction, selection of technology, opportunities and threats, required resources, acquisition modes, competences of the organization, and knowledge management (Burgelman, Christensen, & Wheelwright, 2003; Chiesa & Mazini, 1998; Hax & Majluf, 1991; Porter, 1985b; Santos et al., 2015). Especially the selection of technology offers various options such as scoring or utility models, analytical hierarchy process, rankings, fuzzy techniques, or mathematical programming methods. Furthermore, the strategy defines whether a company seeks technological leadership for selected technologies or positions itself as a follower. As acknowledged by Lieberman & Montgomery (1988, p. 52), "[…] for any given firm, the question of whether early or late entry is more advantageous depends on the firm's particular characteristics. […] If one firm has unique R&D capabilities while the other has strong marketing skills, it is in the interest of the first firm to pioneer and the second firm to enter at a later date. Both may earn significant profits entering in this sequence". Therefore, whether a leader- or followership is most appropriate depends on the firm's resources.

Technological investments are typically accompanied by follow-up costs. First, continuous technical changes and adaptations are necessary throughout the operational lifecycle of machines or infrastructure (Bell & Pavitt, 1993, p. 161). Second, general and preparatory training of employees to maintain and improve their skills is crucial. Training of employees accelerates the adoption of technologies and improves the probability of effective technology commercialization (Argote & Hora, 2017; Zahra & Nielsen, 2002). Moreover, Tyre (1991), Amoako-Gyampah & Salam (2004) and Sohal et al. (1999) proved that training prior to the implementation of a new technology significantly affects gains in performance and employee's acceptance. Further research in the context of "technology acceptance models" and "theory of acceptance and use of technologies" examine the acceptance behavior and utilization of (new) technologies by humans (e.g. Davis, 1986; Davis, Bagozzi, & Warshaw, 1989; Venkatesh & Bala, 2008; Venkatesh & Davis, 2000; Venkatesh, Morris, Davis, & Davis, 2003).

2.6.1.3 Advanced manufacturing technology (AMT)

AMT is a special form of technologies that evolved in the mid-1980s. It represents a wide range of "modern, mainly computer-based systems as well as new organizational practices" (Small, 2007, p. 513). All computer-enhanced and numerically controlled systems and technologies such as CAD or CAM fall into this category. According to Tracey, Vonderembse, & Lim (1999, p. 413), "investments in AMT such as computer-aided design and computer numerical controls provide resources that enable a firm to respond to rapid market change and adapt to shorter product life cycles by designing and producing high-quality, custom designed products". Since then, AMT has widely been considered as a competitive advantage and many scholars have studied this research field (e.g. Boyer, Leong, Ward, & Krajewski, 1997; Cagliano & Spina, 2000; Gouvea da Costa & Pinheiro de Lima, 2008; Kotha & Swamidass, 2000; McDermott & Stock, 1999; Noori, 1990; Rahman, 2008; Small, 2007; Small & Yasin, 1997; A. S. Sohal, Sarros, Schroder, & O'Neill, 2006; Sun, 2000; Swink & Nair, 2007; A. J. Thomas, Barton, & John, 2008; Tracey et al., 1999).

2.6.2 Digitalization

2.6.2.1 Definition and focus

In recent years, the emergence of the *Internet of Things* (IoT) was the starting point for a digitalization process "as technologies and communication solutions are increasingly integrated, from standalone devices in a network to an intelligent object network in which the physical and virtual worlds interact" (Kache & Seuring, 2017, p. 11). The term goes back to Kevin Ashton who created it to describe the increasing impact and intelligence of objects (Ashton, 2009). Since then, IoT and digitalization as technologically driven and enabled concepts received great attention in theory and particularly in practice[4]. Nowadays, it is among the most significant trends transforming our society and influences daily life as well as most industries (Hagberg et al., 2016; Legner et al., 2017; Yoo, 2010). Digitalization affects products, services, industries, organizations, processes, individuals, and others (Brynjolfsson & McAfee, 2014). By "combining digital technologies such as sensors, RFID [Radio Frequency Identification] tags, and cloud computing with non-digital products and services may give products and services new properties and provide significant opportunities for new innovation" (Abrell, Pihlajamaa, Kanto, vom Brocke, & Uebernickel, 2016, p. 324). The potential benefits of digitalization for organizations are multifaceted and "include increases in sales or productivity, innovations in value creation, as well as novel forms of interaction with customers" (Matt, Hess, & Benlian, 2015, p. 339). Therefore, it can effect complete business transformations or reshape existing business models (Downes & Nunes, 2013).

[4] *Digitalization, IoT, smart manufacturing, Industrie 4.0, industry 4.0, industrial internet, industrial internet of things, second machine age, fourth industrial revolution, Industrie 2025 (Switzerland), or "made in China 2025" are based on almost identical constructs. Hence, the term digitalization is used as a substitute for all other related constructs and wordings in the context of this research.*

Digitalization is driven by the ideas of market-pull and technology-push. Market-pull assumes a customer demand-induced technical solution (M. Peters, Schneider, Griesshaber, & Hoffmann, 2012, p. 1297). For instance, changes in customer's attitudes, behavior, or expectations result in customized goods as well as resource-efficient and sustainable products (E. Abele & Reinhart, 2011; Schreckling & Steiger, 2017). Different technological solutions in the context of digitalization can help to satisfy these new demands. As the impulse comes from customer groups or individuals, a market orientation reduces the likelihood of market failures, but can also lead to a more short-term profit oriented approach (T. Abele, 2006). In contrast, technology-push is characterized as a supply-side-driven approach. The impulse is caused "by the application push of a technical capability" (Brem & Voigt, 2009, p. 355). The idea is to commercialize new developments and products. The main advantage of a technology-oriented strategy lies in a higher potential of technical success, which, however, is accompanied by an additional risk of demand and sales uncertainty (T. Abele, 2006; Brem & Voigt, 2009). Technologies within the scope of digitalization are mainly supply-side-driven. In fact, digital technologies become cheaper, lighter, smaller, faster, and achieve higher capacity rates (Brynjolfsson & McAfee, 2014; Porter & Heppelmann, 2014, p. 68). This allows the penetration of markets and exploitation of digitalization advantages (Schreckling & Steiger, 2017). According to Bauernhansl (2014, p. 30), it is technology-push that spurs the idea of the digitalization. In direct comparison, market-pull is a replacement of existing products or fulfilment of customer demands, whereas technology-push is a creative or destructive approach (Walsh, Kirchhoff, & Newbert, 2002). Both approaches drive the diffusion of digital technologies.

Focusing on the manufacturing industry, digitalization is known as "active manufacture-based technologies and systems that can respond to complicated and diversified situation of manufacturing field in real-time" (Kang et al., 2016, p. 111). From a technological point of view, digitalization is based on digital technologies and the internet. The dissemination of digital technologies enables companies to benefit from productivity gains, new business cases or enhanced processes (Liu et al., 2011, p. 1728; Porter & Heppelmann, 2014, p. 67). Digitalization can be discussed from two perspectives (Berghaus & Back, 2016, p. 2; Yoo et al., 2010, p. 725), namely:

- Internal perspective: Exploitation of digital technologies to improve internal process innovations and efficiency in different departments and functions of a company. This also includes enhancements in a company's (internal) value network.

- External perspective: Enhancement of physical products or services with digital abilities due to digital innovations. In other words, "digital technologies complement and/or enrich existing products and services and allow building entirely new business models" (Legner et al., 2017, p. 302).

This research will concentrate on the internal perspective of digitalization (i.e. digital technologies) and direct value creating processes such as assembly or production in manufacturing companies. Digital services, products or business models are not addressed.

Although most researchers use the terms *digitization* and digitalization interchangeably, it is advisable to distinguish between them. *Digitization* is a technical process and refers to the conversion of analog to digital information, signals and processes (Loebbecke & Picot, 2015, p. 149). This understanding has existed since the first computers emerged. Whereas *digitization* is limited to technological aspects, "the term digitalization has been coined to describe the manifold socio-technical phenomena and processes of adopting and using these technologies in broader individual, organizational, and societal contexts" (Legner et al., 2017, p. 301). Following this argumentation, the term digitalization is more appropriate for this research as it extends the merely technical view of technologies to more interdisciplinary and socio-technical circumstances.

2.6.2.2 Industrie 4.0

In the German speaking area, digitalization of manufacturing processes is also known as *Industrie 4.0*. It is based on the emergence of digital technologies (Strange & Zucchella, 2017). The term *Industrie 4.0* was introduced by the German government in 2011 and symbolizes the fourth industrial revolution (Kagermann, Wahlster, & Helbig, 2013; Kang et al., 2016; Lu, 2017; Magruk, 2016; Prause & Weigand, 2016). Nonetheless, the progress of *Industrie 4.0* is more an evolution than a revolution. The term is mainly used in practitioner's science and, has so far not been established in scientific literature. Obermaier (2016, p. 8) notes that *Industrie 4.0* describes a form of industrial value creation that is characterized by the digitalization, automation and connection of all actors involved in a value creation process and affects processes, products or business models of industrial companies. Sendler (2018b, p. 27) specifies that "*Industrie 4.0* is an integral part of general digitalization", but limited to manufacturing-related activities.

Apart from technological aspects and the decentralization of intelligence and control, the paradigms – horizontal, vertical and end-to-end integration – are basic principles of *Industrie 4.0*. Horizontal integration refers to the connection of different production and IT systems as well as the exchange of information (Siepmann, 2016a, p. 29). This can be realized both within single sites of a company or within a value creation network (e.g. from supplier to manufacturer or to customer). The vertical integration focuses on the immediate access to field and company-relevant information within a company. It addresses the connection of different production and IT systems across a company and leads to the dissolution of hierarchical structures and the automation pyramid (e.g. field level, process control level, enterprise level) (Siepmann, 2016a, p. 29). The vertical integration significantly enhances transparency. The end-to-end integration (digital continuity) describes the uninterrupted engineering process across the entire value chain and the product's life cycle.

2.6.2.3 Computer-Integrated-Manufacturing (CIM)

Digitalization is often linked to the CIM concept of the 1970s and 1980s. The idea of CIM was complete automation, planning and control at every stage of the value chain. Until today the approach has not been fully implemented due to employee resistance, missing standards, lack of technologies, and organizational incompatibilities (Prause & Weigand, 2016). Some critics assume that digitalization approaches will have similar limited success. In contrast to CIM, however, availability and maturity of technologies and IT systems has steadily developed. These technologies can collect and provide data and information in real-time. Furthermore, today's technical systems are cheaper and more reliable (Prause & Weigand, 2016). Another difference to CIM is the role of humans. While the CIM concept aimed at human-free manufacturing, employees will still play an essential role in the digital era (Siepmann, 2016a). Neither in times of CIM nor today, is it imaginable and reasonable to operate processes without a human's input and decisions. CIM and lean management activities can be seen as a starting point for digitalization. However, digitalization is not just a new edition of the CIM concept. Although the basic idea behind both concepts is comparable, the implementation will take place in different ways.

In summary, digitalization or *Industrie 4.0* are not really new paradigms. Most approaches are a recombination or technological advancement of existing concepts from the fields automation, CIM or lean management (A. Roth, 2016, p. 6). Regarding this research, the understanding and scope of digitalization is limited to the internal perspective and, especially, digital technologies in manufacturing companies.

3 Interrelations of digital technologies and plant roles

The purpose of chapter 3 is to understand the impact of digital technologies on plant roles and manufacturing networks. With reference to Ferdows, Vereecke, & De Meyer (2016, p. 63), the "emergence of new competitors and new technologies, continue to require adjusting the structure of these networks constantly". To examine the research topic in detail, existing and most discussed digital technologies in manufacturing are identified. First, chapter 3.1, introduces the specific characteristics of digital technologies. A description model is developed for a better understanding. In chapter 3.2, potential digital technologies are identified, explained and a classification is derived. Afterwards, digital technologies are filtered and ranked according to different criteria in chapter 3.3. Finally, chapter 3.4 explains the impact of digital technologies on selected plant roles. The findings can be seen as the first step to answer sub-RQ1.

Some findings in this chapter have been partly published in former or amended versions in the following outlets:

- *Benninghaus, C., & Budde, L. (2018). Digitale Technologien standortübergreifend nutzen – Schubkraft für kollektives Wissen. Industrieanzeiger, 140(7), 28-29.*
- *Benninghaus, C., Budde, L., Friedli, T., & Hänggi, R. (2018), Implementation drivers for the digital industrial enterprise, in: International Journal of Production Economics, In review.*
- *Benninghaus, C., Elbe, C., Budde, L., & Friedli, T. (2018). Digital Technologies – Evolution of production in high-wage countries. Final report. Institute of Technology Management at the University of St.Gallen, St. Gallen.*
- *Benninghaus, C., Wenking, M., & Friedli, T. (2016). Benchmarking Industrie 4.0: Wie agieren erfolgreiche Unternehmen? IM+io, 3, 75-80.*
- *Friedli, T., Benninghaus, C., Elbe, C., & Remling, D. (2018). Swiss Manufacturing Survey – A national Study. Final Report. University of St.Gallen, St. Gallen.*
- *Lorenz, R., Benninghaus, C., Netland, T. H., & Friedli, T. (2018). Open process innovation and digitalization of manufacturing. In 25th International Annual EurOMA Conference. Budapest, Hungary, June 24-26, 2018.*

3.1 Characteristics of digital technologies in manufacturing

In recent years and as proposed for the next years, manufacturing has become and will further become digital, integrated and intelligent (F. Tao et al., 2011). These characteristics are distinctive for digital technologies. Similar to the definition of the term technology, there are no precise definitions and specifications of digital technologies (Janasz, 2018, p. 92). The understanding of digital technologies depends on the business and varies for different industries. Digital technologies can be systems, tools, machines, platforms, components, or applications (von Briel, Davidsson, & Recker, 2018, p. 49). Such technologies are transforming a firm's capabilities, processes, strategies, products, and service offerings (Bharadwaj et al., 2013, p. 471). Thus, the application, integration and exploitation are important steps, but also key challenges to improve productivity, enhance innovations and reduce costs (Hess et al., 2016). Liu et al. (2011, p. 1728) call the integration of digital technologies in a company's business processes "digital transformation". A more detailed working definition is derived in the subsequent chapter.

3.1.1 Attributes

Researchers put forward several attributes to describe the characteristics of digital technologies. For instance, Bharadwaj et al. (2013, p. 471) depict digital technologies as arrangements of *computing, communication, information,* and *connectivity* features. In this context, *computing* is the ability to process internal and external input and act accordingly. For example, a collaborative robot notices that an employee is inattentive and moves away or stops operating. The attribute *information* means that all kind of information, also from the internet, can be processed by the technology. *Communication* abilities enable a technology to interact with other systems, receive from and share information with the internet or humans, by using specific transmitter, antennas or other such components. Last, *connectivity* is a precondition for information processing and communication as it is based on standard protocols. *Connectivity* becomes even more important in today's plant infrastructure as most providers and systems have their own operating systems, ports and connections, which are not compatible to other systems of foreign providers.

Yoo et al. (2010) underline the difference between digital and conventional technologies. The "three unique characteristics: the *reprogrammability*, the *homogenization of data*, and the *self-referential* [are the] nature of digital technology" (Yoo et al., 2010, p. 726). *Reprogrammability* enables a digital technology to be adjusted to changing conditions or new tasks. Hence, it becomes malleable and can perform different jobs and fulfil new requirements, although the hardware remains the same (e.g. smart robot). The second attribute, *homogenization of data*, clarifies that a technology can process, store, share, and display all kind of data and information, which it receives from the internet, other machines or humans. *Self-reference* is the ability to connect to other systems and create (local) networks.

In a more general way, López, Ranasinghe, Patkai, & McFarlane (2011) name *identity, sensing, actuation, decision-making*, and *networking* as features related to smart objects, which are understood as digital technologies or products. First, it has a unique *identity* as well as storage. Moreover, it is aware of its condition and environment due to a *sensing* ability. Consequently, such an object can *act* and make *decisions*. This also includes the ability to control and steer other objects. Last, it can *network* with other objects or technologies and share information. These characteristics are optional and at least two or more attributes are necessary to constitute a smart object. However, some attributes cannot stand alone. For example, *sensing* and *decision-making* are closely linked or the *network* ability is not useful without having a unified *identity* (López et al., 2011, p. 285).

Kallinikos, Aaltonen, & Marton (2013, p. 357) define digital artefacts or technologies as *editable, interactive, reprogrammable,* and *distributable*. *Editability* can be achieved through adding to, erasing from or rearranging information and abilities. These kinds of modifications allow an object to be adjustable to changing conditions. Therefore, such objects are “open” and *reprogrammable*. While *editable* describes a simple reorganization, it can be fully modified by external operations based on its *reprogrammability*. Being *interactive* allows the objects to communicate and process input from the environment. Last, *distributed* means that the objects have access to physical information as well as cyber information from the internet or other information sources. Von Briel et al. (2018, p. 49) combine the definitions of Kallinikos et al. (2013) and Yoo et al. (2010) by summarizing that “digital technologies can become *malleable, editable, self-referential,* and *interactive*”.

Yoo (2010, p. 225) adds to the definition by Yoo et al. (2010) and mentions the attributes *addressability, associability, programmability, sensibility, communicability, memorability,* and *traceability* of digital artefacts and technologies. The idea is that each technology is unique and individually *addressable* by a RFID chip, barcode or microprocessor. Another attribute, *communication*, reflects the ability to interact with other systems, humans or the internet. *Programmability* is a characteristic of digital technologies, which makes them malleable and allows modifications. *Sensibility* makes a technology context aware as it receives and processes information from the environment through sensors. Moreover, the *memorability* allows the recognition of past actions, locations and events. These memories can be stored locally or online. This results in the *traceability* characteristic of digital technologies. It can be tracked and traced throughout its lifecycle. In the best case, a digital technology becomes *associable*, which means more decentralized and less dependent on central steering and control (Yoo, 2010, p. 226). As an outcome, the technology would be able to adjust itself and make decisions without any intervention from an operator.

Another frequently used characterization is the 5C (*connection, conversion, cyber, cognition, configure*) level architecture by Lee, Bagheri, & Kao (2015, p. 20) to describe cyber-physical systems (CPS) as a manifestation of digital technologies. *Connection* is necessary to acquire data from the processes. It can be directly collected by the sensors of a machine or from manufacturing (IT) systems. Afterwards, data is *converted* into information. On the *cyber* stage, all applicable information is gathered, analyzed and evaluated. This is important to monitor and control a fleet of machines. It allows a single machine to align itself. With the help of the *cognition* ability, the information is prepared and presented to the operators to support them in their decision-making. Finally, *configure* refers to the interaction of the physical machine with the cyber space to create self-adaptive and configuring systems.

Kühnle & Bitsch (2015, p. 56) list nine functionalities namely *modularity, heterogeneity, scalability, context awareness, autonomy, interoperability, networkability, acceptance of existing boundaries,* and *network participation*. First, digital technologies should be *modular* and *scalable*, so that machines and systems can be delayered into modular units. Typically, digital technologies are also *heterogeneous*, which results in incompatible systems. The need for using standardized interfaces and interoperationality for digital technologies becomes increasingly pertinent. Further, *context awareness* is a crucial factor. As mentioned beforehand, a context aware digital technology knows its state, location or condition. In combination with its *autonomy*, it can modify and adjust its state and take actions. Furthermore, it can interact and communicate with other objects in the network. This *networkability* allows for a collaboration of digital objects and is supported by sensing and acting components. Accordingly, a digital technology knows its technical and network boundaries and actively interacts with other digital technologies in the local network. However, the precondition is interoperationality. Similarly, Mittal, Khan, Romero, & Wuest (2017, p. 5) identified the following characteristics: *context awareness, modularity, heterogeneity, compositionality,* and *interoperationality*.

Chaves & Nochta (2010, p. 26) characterize the properties of smart items as "*information storage, information collection, communication, information processing,* and *performing actions*". Sensors, RFID or other techniques can *collect* internal or external information. Locations, temperature, expiry date, emissions, or humidity are only a few measurable parameters, which can be recorded and have a direct influence on technology. As a smart item has computing power, the information can also be *processed* directly and put into action. Thus, such technologies can control and change their own state or actively interact with other systems or humans. The ability to *communicate* supports this process and gives the technology a certain level of intelligence. Such smart items are also able to *store* data (Chaves & Nochta, 2010, p. 27).

From another point of view and with reference to Ning & Hu (2012, p. 1233), digital technologies comprise the four dimensions *body, processing, intelligence,* and *sociality*. First, the *body* includes hardware components such as sensors or functions for network access. These are standard components, which shape the physical embodiment of digital technologies. Second, the *processing* dimension contains analysis, transmitting, security, or storage of information. It is a precondition for the third attribute *intelligence*. *Intelligence* is understood as the ability of autonomous decision-making, intelligent control or self-organization. As a result, the fourth characteristic, *sociality*, exemplifies actions according to relevant laws, moral decisions or interactive management with humans or objects.

Zittrain (2008, p. 71) proposes five attributes of generative technologies, which can be understood as digital technologies from today's perspective. First, *leverage* embodies how extensively a technology can fulfill certain tasks. An example are computers, which can be used for calculations, graphic design, office tasks, etc. Hence, *leverage* describes the capability of a technology to perform possible activities. Second, *adaptability* describes the feature of how easily a technology can be modified to perform new activities. A technology has a high level of *adaptability* if it comes with several features and can perform even more tasks in the future. The third attribute, *ease of mastery*, refers to the idea of how easily humans or (new) employees can understand and make use of this technology. Depending on the qualification and the know-how of employees, a technology can be either used directly or only after finishing extensive trainings or education programs. For example, people learn to work with a collaborative robot relatively fast, but the control of a drone can become more challenging. Even though the required competences to master a technology may not be present in the beginning, they can be learned. *Accessibility* refers to the amount of effort required to access a technology. Governmental regulations, trade barriers or taxes can limit access to such technologies. Zittrain's (2008, p. 73) last characteristic, *transferability*, deals with the chances of transferring a technology to other business units, plants or making it easier for non-experts to master operations. In contrast to other authors, Zittrain (2008) neglects the attributes *connectivity* or *communication*.

3.1.2 Development of a description model

After identifying different attributes of digital technologies, the following figure 4 summarizes the findings in form of a description model. With reference to Mylopoulos (1992) such a model represents "[…] some aspects of the physical or social reality for the purpose of understanding and communicating" (cf. Mettler, 2011, p. 86) and therefore, it is useful to get a common understanding of the attributes of digital technologies. The author designed universal building blocks, which are applicable regardless of the specifics of an individual digital technology. Thus, all new technologies that have the potential to change conventional production can be addressed by the model.

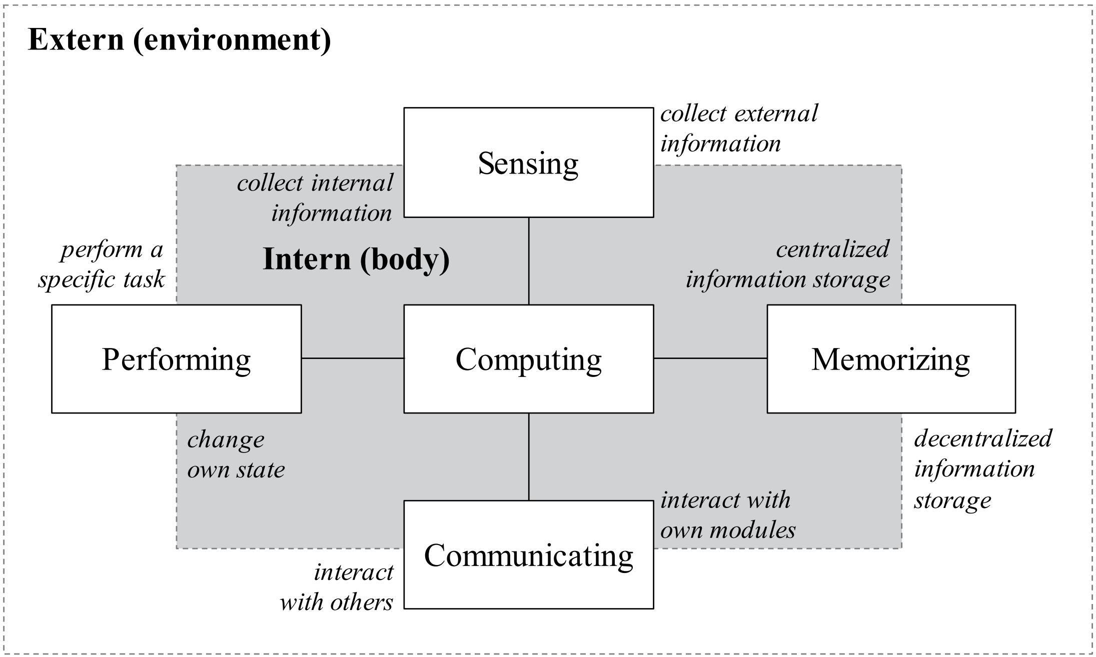


Figure 4: Description model for digital technologies in manufacturing (own illustration)

The description model provides transparency, reveals interdependencies and the building blocks form an integral system. A digital technology has a physical body (grey area), is embedded within a physical environment and has connections to other physical objects, humans or non-physical areas such as the internet. The first characteristic is *sensibility*, which makes a digital technology context aware. It can collect information about itself and from the environment. Hence, a digital technology can recognize its operation state, location, condition, and external influences. In short, this ability is known as self-awareness. Another element is the *computing* and reprogrammability ability to manage and process information. This characteristic contributes to a certain autonomy of digital technologies. Because *sensing* and *computing* are combined, a digital technology can evaluate internal and external influences. Such autonomy can be used for *performing* actions and tasks as well as for controlling and modifying its own state. Therefore, digital technologies can affect themselves and manipulate other objects and the environment. Similarly, digital technologies are characterized by their *communication* ability. They interact with their own modules as well as with external systems, machines or humans. However, this network participation requires interoperationality and a minimum of sociality. Finally, the distribution and storage of information (*memorability*) is a typical attribute of digital technologies. Information is stored either centralized (e.g. on the object) or decentralized (e.g. online, server). Except for the computing ability, all other characteristics affect both internal (body) and external (environment) factors.

In summary, digital technologies are defined for the purpose of the present research as *machines, components or systems that have a sensing, computing, performing, communication, and memory ability as well as the potential to contribute to and change conventional manufacturing from a production-specific perspective.*

3.2 Digital technologies in manufacturing

The majority of digital technologies in manufacturing have a *disruptive* effect. According to Danneels (2004, p. 249), "a *disruptive* technology is a technology that changes the bases of competition by changing the performance metrics along which firms compete". Gal, Lyytinen, Carlo, & Rose (2007, p. 2) identified three characteristics of such *disruptive* and technological innovations. First, such technologies differ from existing alternatives, processes or structures. This can be seen in the context of robotics or additive manufacturing (AM). Both technologies enable new forms of value-adding activities, which other alternatives do not facilitate. Second, new cognitive frames become important. The application and usability of new technologies change the traditional forms of working (Brenner et al., 2014, p. 59). Third, *disruptive* technologies are affecting future innovations and transform processes or structures. For example, AI solutions are already influencing R&D processes and collaborative robots are reinventing cooperation and working structures on the shop floor.

3.2.1 Identification of digital technologies in manufacturing

The following table 7 provides an overview of the 30 most discussed digital technologies related to manufacturing. Only a limited number of publications can be found that cover a holistic view of digital technologies. Therefore, also three non-scientific publications are included (5, 6, 20). These practical publications present a broad scope of technologies, are renowned and widely read in management circles. Publications that are limited to single technologies or applications have not been considered. This approach allows to create a comprehensive list of digital technologies.

The results of the literature review and the relevance of the identified technologies have been discussed with industry experts. An interesting finding is that the mentioned digital technologies address different stages of expansion. For example, a smart robot or mobile device for shop floor applications is composed of several sensors or software techniques, which are also mentioned as separate digital technologies. Therefore, single technologies as well as technological concepts are both addressed by the review.

Table 7: Digital technologies related to manufacturing (own illustration)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
4D printing					•															•
Additive manufacturing	•	•	•	•	(•)	•		•	•	•		•	•	•	•	•	•			•
Artificial intelligence					•						•	•			•			•		•
Augmented reality	•	•	•		•	•		•	•	•			•			•			•	•
Automated guided vehicles		•	•		•				•						•					
Big Data analytics	•	•	•	•	(•)	•	•	•	•	•	•		•	•	•	•	•	•	•	•
Blockchain		•			•										•					•
Cloud computing	•	•	•	•	(•)	•	•	•		•		•	•		•	•		•	•	•
Cyber-physical systems		•	•	•			•	•	•	•	•	•	•	•	•		•	•	•	•
Digital/cyber security		•	•	•	(•)			•	•	•			•		•					•
Digital twin					•										•					•
ERP	•		•	•			•	•		•			•			•			•	
Hologram				•				•												
Industrial automation	•			•			•			•		•			•		•	•		•
Internet of Things	•	•	•	•	(•)	•	•	•	•	•	•	•	•	•	•		•	•	•	•
M2M			•		(•)											•			•	•
Machine learning					•				•	•	•				•					•
MES	•		•	•				•	•	•						•			•	
Mobile computing/devices		•	•			•	•		•						•					•
PLM				•		•		•			•									
RFID	•	•	•	•			•	•	•		•				•	•		•	•	
Sensors & Actuators	•	•	•	•		•	•	•	•	•	•		•	•	•		•	•	•	•
Smart robotics		•	•	•	•				•	•		•	•		•		•	•		•
(Smart) collaborative robotics	•		•	•					•	•								•		•
Smart dust					•															•
Social media technology	•																			•
Track & trace			•	•		•		•							•					
UAV/drones	•	•			•										•		•			
Virtual reality	•		•		•			•	•	•						•			•	•
Wearables		•	•		(•)	•			•						•					•

(1) (Hänisch, 2017); (2) (Hofmann & Ruesch, 2017); (3) (Huber, 2016); (4) (Kang et al., 2016); (5) (Gartner Inc., 2017), Note: The brackets symbolize that the technology was listed in a former Gartner Hype Cycle from 2014-2016; (6) (Griessbauer, Vedso, & Schrauf, 2016); (7) (Lu, 2017); (8) (Mittal et al., 2017); (9) (Neugebauer, Hippmann, Leis, & Landherr, 2016); (10) (Obermaier, 2016); (11) (Pagoropoulos, Pigosso, & McAloone, 2017); (12) (Paritala, Manchikatla, & Yarlagadda, 2017); (13) (Saucedo-Martínez, Pérez-Lara, Marmolejo-Saucedo, Salais-Fierro, & Vasant, 2017); (14) (Schönsleben, Fontana, & Duchi, 2017); (15) (Schwab, 2016); (16) (Siepmann, 2016b); (17) (Strange & Zucchella, 2017); (18) (Thoben et al., 2017); (19) (Wagner, Herrmann, & Thiede, 2017); (20) (World Economic Forum, 2017)

Only digital technologies, which were mentioned at least twice in literature are considered and concepts (wordings) based on similar technology are consolidated. As an example, smart robotics also covers autonomous, advanced or intelligent robotics.

This overview is not conclusive as new digital technologies permanently emerge and the technological maturity as well as relevance of technologies varies across industries and over time. A short description of each technology can be found in appendix F.

3.2.2 Classification

Digital technology has turned out to be a broad and complex terminus. Therefore, it is not surprising that many practitioner driven approaches exist for classifying and clustering digital technologies (e.g. Griessbauer et al., 2016; Wagner et al., 2017; World Economic Forum, 2017). However, no uniform classification has become generally accepted. In general, a classification is a set of criteria to compare and structure technologies (Aunger, 2010; H. Lee et al., 2011). In the following, a holistic overview of existing approaches is illustrated. Schuh, Klappert, Schubert, & Nollau (2011) provide a comprehensive summary of technology classification schemes. Figure 5 summarizes these schemes.

Field of application / Function	Product-, production-, service-, or material-technology
Interdependence	Integrated- or stand-alone; Complementary-, competitive-, or substitution-technology
Industry related scope of application	Crossover technology, industry-specific technology
Intra-company scope of application	Core competence-, low-competence-technology
Degree of product-relation	Core- or supporting technology
Life-cycle phases	Emerging-, pacing-, key-, or base-technology; Early adopters, early/late majority, laggards

Figure 5: Technology classification (adapted from Gerpott (2005) and extended by the author)

On the one hand, a classification according to the *field of application* like product, production, service, or material technology is possible. On the other hand, *interdependencies* are useful to classify technologies. For example, laser could be a substitution technology for electrical discharge machining. Another classification is related to the *scope of technology*, which can be either industry specific (e.g. vacuum technology for semi-conductors) or cross-industry relevant like communication technology. On an intra-company level, core competence and lower competence technology can be distinguished. Also, a generalized approach like core and supporting technologies can be useful. An alternative classification is based on *lifecycle phases* and was developed by the consultancy Arthur D. Little. They define *emerging technologies, pacing technologies, key technologies,* and *base technologies*. The classification is supposed to be helpful when companies are evaluating current and future available technologies with regard to their competitive relevance (Binder & Kantowsky, 1996, p. 93). Another classification is the S-curve concept developed by Foster (1986).

Considering the possible classification approaches, digital technologies are grouped into the following categories according to the *field of application* and *core-/supporting* technologies to bundle the identified technologies:

- Automation and manufacturing technology (e.g. AM, collaborative robotic, smart robots, automated guided vehicles, UAVs)
- Data analytics and ICT (e.g. AI, ERP, MES, cloud computing, machine learning, Big Data analytics)
- Human-machine interfaces (e.g. AR, wearables, VR, hologram, mobile devices)
- Embedded systems (e.g. sensors and actuators, M2M, smart dust, cyber security, RFID, track & trace)

A similar classification has been introduced by Obermaier (2016, p. 14). It is important to mention that there is no unambiguous selective classification, since several technologies can be assigned differently or affect more than one technology class. Thus, the four classes are based on the primary attributes of digital technologies.

3.2.3 Summary and implications

Although many technologies, ideas and concepts of digitalization are not new, numerous business cases have proven that digitalization can have a meaningful impact on the transformation and success of companies in manufacturing industries (Bauernhansl, 2014; Brynjolfsson & McAfee, 2014; Huber, 2016; Kang et al., 2016; A. Roth, 2016; Sendler, 2018c; Westkämper, Spath, Constantinescu, & Lentes, 2013).

The author emphasizes that there is no key technology, which is necessary or should be implemented by each company for mastering digital transformation successfully. The identified 30 technologies are an integral part of digitalization, however, some of them only create value if they are combined with other technologies. A partial use of these technologies rather results in an “Industrie 3.x concept” (Graef, 2016, p. 81). Moreover, companies normally cannot implement any of these technologies in a standardized way. An individual analysis and evaluation of each technology is inevitable, as not all industries or companies can benefit from each technology. Hence, technology selection is one of the most crucial tasks for the industrial management as technologies typically cover more than 30 percent of the capital spending of a company (Shen et al., 2010, p. 151,152). However, the value of a technology is rarely based on the technology itself but rather on its ability to improve production and business processes (Benninghaus et al., 2016). Although these technologies are frequently labeled as "digital technologies" in literature, the next chapter will show that not all of the 30 identified technologies match with the underlying definition and other criteria.

3.3 Criteria for filtering digital technologies

The idea of this research is to take the general term technology to another level and concentrate on single (digital) technologies as it is not possible to address all identified technologies in detail. Therefore, different screens are used to filter and select the most appropriate digital technologies for this research.

This kind of exclusion principle follows the funnel models of Wheelwright & Clark (1992). Funnel models serve as tools for identifying and selecting alternatives. Wheelwright & Clark (1992) have developed two generic models that support the selection of alternatives based on different criteria within a longer process. Figure 6 presents the models.

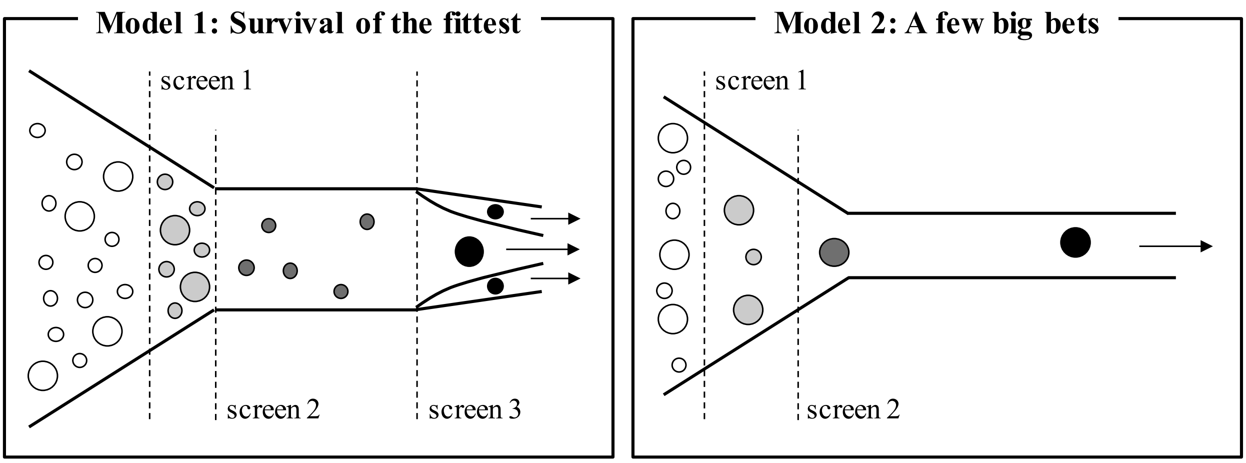


Figure 6: Funnel models (adapted from Wheelwright & Clark, 1992, p. 119)

Both models build on a broad information base. Following the "a few big bets" model, alternatives are selected relatively quickly. A characteristic of this variant is the decision for a defined alternative in the funnel neck. This evaluation is informally structured and based on gut instincts. Contrasting, the "survival of the fittest" model is a formal authorization and allows a better focus on an alternative due to a sequence of screenings.

At each screening stage alternatives are systematically evaluated and sorted out. Thus, “the essence of the model 1 funnel is a technology-driven survival of the fittest” (Wheelwright & Clark, 1992, p. 118). This approach is adopted for this research. The different screening criteria will be presented within the next chapters.

3.3.1 Input from annual study on manufacturing activities in Switzerland

The annual “Swiss Manufacturing Survey” is conducted by the ITEM-HSG (Friedli, Benninghaus, Elbe, & Remling, 2018). The aim is to ascertain current developments and structural changes of the Swiss manufacturing landscape. It addresses manufacturing firms with at least one manufacturing plant in Switzerland. The study allows direct comparison of different manufacturing sectors, economic situations and business performances of individual companies. The following figure 7 outlines the findings of one selected question of the 2018 version of the “Swiss Manufacturing Survey”. The 186 participants were asked which technologies offer the highest potential to (1) secure manufacturing activities in the high-wage location in Switzerland, (2) change the dispersion and configuration of sites, and (3) realign the roles and functions of certain sites. Multiple answers were possible. Although the three questions address different subjects, the order and frequency of responses regarding the potentials of different technologies are comparable.

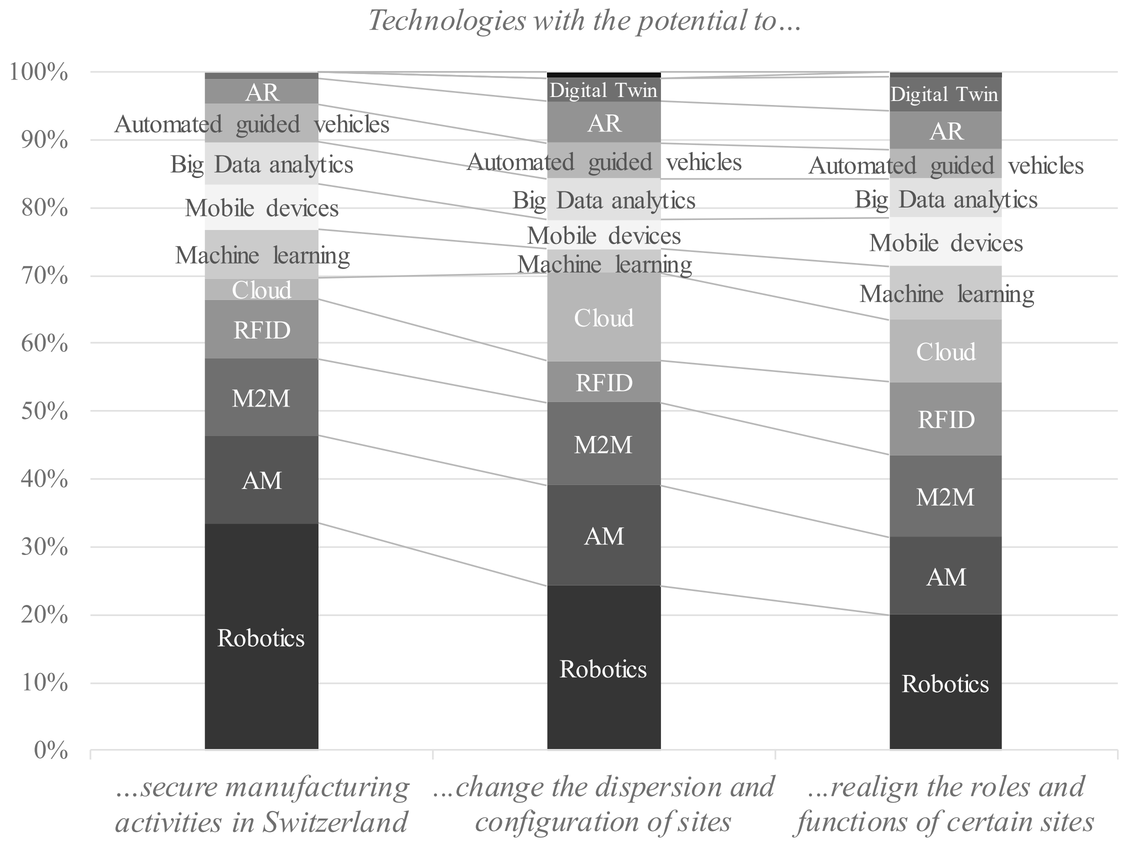


Figure 7: Digital technologies and IMN configuration (adapted from Friedli et al. (2018, p. 53))

First, robotics is supposed to have by far the highest potential to secure manufacturing in high-wage regions (33 percent) and have an impact on IMN configuration (24 percent) and plant roles (20 percent). Especially, increasing automation due to the application of (smart) robotics allows a reduction of direct labor costs and an improvement of local competitiveness. Ranked in second place, AM seems to have a high impact. According to the participants, AM can change the dispersion and configuration of manufacturing sites (15 percent) as it allows an instant and individual production of products at low lot sizes. Although the maturity of AM applications is still limited, this technology is supposed to transform traditional structures and plant roles (11 percent). Technologies belonging to the group of embedded systems such as M2M and RFID are also estimated to have a potential influence on secure manufacturing and change IMN configuration. However, these technologies are supporting other systems more on plant level and not from a network perspective. In contrast, cloud computing has a high potential to effect IMNs and change the dispersion of plants and configurations (13 percent) from an overall network perspective. Other technologies such as machine learning, mobile devices, Big Data analytics, automated guided vehicles, AR, or digital twins are less mentioned. The reasons are the limited implementation levels and related experience with these technologies. Blockchain technology and UAVs were only checked ones each.

The figure gives a first impression of the potential impact of different technologies on IMN configuration and plant roles. However, the survey results are not a central argument for selecting digital technologies according to the funnel model (figure 6) as the reasons for the respective choice are not always comprehensible. Although several companies were asked for the details for their individual estimation in the questionnaire, the responses are rarely well founded. Thus, the findings from the study serve more as a basic idea and orientation for understanding the relevance and impact of digital technologies.

The author is convinced that these results from Switzerland might mirror the convictions held by management in other companies located in high-wage countries in Western Europe.

3.3.2 Technology readiness level

The first filter criterion is the Technology Readiness Level (TRL). TRL is a measurement system or systematic metric to assess and evaluate the maturity of a technology (Mankins, 1995). Since the NASA invented TRL initially in the 1970s for their space mission programs, it has been modified and adopted by many industries and governmental institutions (e.g. US Department of Defense, European Union's Horizon 2020 program). Nowadays, TRL supports researchers, engineers and managers in mutual understanding, communicating technology status or defining deliverables (Mankins, 2009; Sadin, Povinelli, & Rosen, 1989). Most TRL versions refer to Mankins' (1995, 2002) nine-point scale, which measures the maturity of a technology from "basic research" to "in full operation". The following list is a generalization of the original nine-point TRL scale as especially TRL_{7-9} contained aerospace terms (L. Tao, Probert, & Phaal, 2009):

- TRL_1: Basic principles observed and reported
- TRL_2: Technology concept and/or application formulated
- TRL_3: Analytical and experimental critical function and/or characteristic proof of concept
- TRL_4: Component and/or breadboard validation in a laboratory environment
- TRL_5: Component and/or breadboard validation in a relevant environment
- TRL_6: System/subsystem model or prototype demonstration in a relevant environment
- TRL_7: System prototype demonstration in a (operational) environment
- TRL_8: Actual system completed and qualified through test and demonstration
- TRL_9: Actual system proven through successful mission operations

Typically, TRL is applied on single company level. To use it on a broader, inter-company and industry level, the TRL stages are clustered into three groups, which makes it easier to determine the TRL of different technologies. The first group ranges from TRL_{1-3}, the second from TRL_{4-6} and the third from TRL_{7-9}. For instance, if companies are employing a specific technology in their manufacturing process, it will be put into group III – even if other manufacturing companies are not applying this technology or are on a less developed stage. The following TRL evaluation is based on literature, expert interviews, findings from an industry study (Friedli et al., 2018), a benchmarking project conducted by the ITEM-HSG (Benninghaus, Elbe, et al., 2018) as well as on the experience and knowledge base of the author.

Most digital technologies mentioned in literature have a high readiness level. Automation and manufacturing technology such as smart robots, collaborative robotic or automated guided vehicles are frequently applied in manufacturing processes of many companies. For example, several case study companies (see chapter 4) use collaborative robotics, smart robots or automated guided vehicles to increase the internal productivity and level of automation. Supplementary, the human-machine interfaces AR, VR, wearables, or mobile devices at shop floor level are frequently applied by companies. Similarly, ERP, MES, or cloud computing are these days standard tools for manufacturing companies. Other embedded systems such as RFID, sensors and actuators are standardized and have been well known for many years. Hence, they all belong to TRL group III. But even though the technologies themselves are very advanced, the successful application and integration varies from company to company.

It is not surprising that not all digital technologies have reached the highest readiness level. Especially technologies associated with data analytics (i.e. AI, machine learning, Big Data analytics, digital twin) are at a lower development stage (TRL group II). Mostly, these technologies are in the stage of prototype demonstration in a laboratory or relevant environment. Even though, for example, Big Data analytics have been previously applied in other industries, the manufacturing sector was not fully able to make use of this technology yet (O'Donovan, Leahy, Bruton, & O'Sullivan, 2015b, p. 2). Furthermore, most machine learning solutions such as spam mail filters or customer behavior management are not pertinent in the context of manufacturing (Schuld et al., 2015, p. 1). Thus far, AM applications are limited to prototype, single product and spare parts production, as AM is "not currently suitable for mass production as unit costs are substantially higher" (Strange & Zucchella, 2017, p. 178). The slow processing time, limited precision and quality can be seen as further barriers for exploiting AM technology (Strange & Zucchella, 2017, p. 178).

Finally, blockchain, 4D printing, hologram, smart dust, and UAVs are even less mature (TRL group I). However, some of these digital technologies are well known in other industries. In particular, blockchain is recognized in financial applications such as crypto-currencies (i.e. bitcoin) or anti-counterfeit solutions for supply chain transactions or contracting (Nofer et al., 2017, p. 185). For manufacturing, only basic principles have been observed and (basic) technology concepts have been formulated. Equally, UAVs are well established in commercial or military use, but not in manufacturing environments. However, first tests confirm the high potential of UAVs for indoor manufacturing locations (Maghazei & Netland, 2017, p. 8). Moreover, holograms are still under investigation although the idea has been known for several decades. At present, holograms are typically a virtual 3D image of an object and cannot be used as a communication technology (Matsushima et al., 2013). Correspondingly, the idea of smart dust can be backdated to the end of the last century, but the technological outcomes are a far cry from the intended object size. Last, 4D printing is a relative new technology, which is being studied in experimental environments by researchers. According to Shin et al. (2017, p. 354) it is a "viable tool in advanced manufacturing and prototyping are expected to expand rapidly in the near future". However, 4D printing is at a very early development stage and, so far, no industrial applications exist. The results of this clustering are shown in table 8.

In fact, digital technologies are continuously developing and therefore this clustering can only be a snapshot in time. It must be pointed out once again that some technologies are being widely used in other industries, but not in the manufacturing sector. As this research does not intent to provide recommendations or benefits for technology usage in manufacturing or evaluate the transferability of technologies to other industries, only technologies of TRL group III are relevant for the progress of this work. Solely mature technologies and systems can affect more than one plant or a manufacturing network as a whole. However, technologies with a lower rating may have an impact on a single site. TRL gives an indication which technologies are in full use in manufacturing industry right now. Although TRL neglects further development perspectives, the method is a suitable filter criterion for pre-selecting relevant technologies in the context of digitalization.

3.3.3 Evaluation based on description model

The description model (figure 4) revealed typical attributes of digital technologies. In the following, the identified technologies from table 7 are discussed in the context of the description model. This process will show that only a few technologies are “real” digital technologies according to the defined attributes. The following discussion and evaluation of digital technologies differs among companies, manufacturing processes, technology type (e.g. different brand or provider) or model variant. This is symbolized by the brackets in table 8. For instance, a smart robot in company 1 made by provider X can differ a lot in its features compared to another company 2 or a provider Y. In this case, the most advanced state of digital technology is considered. Therefore, some attribution results might be imprecise although they are based on the input of industry experts. Table 8 summarizes these findings. Of course, in time and from a different technical point of view, the result might slightly change.

In general, automated guided vehicles in form of autonomous driving systems or forklifts, combine all attributes of digital technologies. These vehicles are context aware, which is enabled by sensors, laser systems or GPS (global positioning system). Their communication skills support this ability as they can receive and send information to other automated guided vehicles, routing or home stations. Therefore, they know their current position or environment and can react to changes accordingly. For instance, modern vehicles can find their way back to their basis for charging. This is made possible by their computing ability. Furthermore, automated guided vehicles stop in case of an unplanned movement of employees or another vehicle to avoid damages. Hence, they have a performing ability, which allows them to manipulate themselves and the environment.

Finally, data is synchronized with a server or online to coordinate a vehicle fleet (cf. memorizing).

Likewise, UAVs and drones are classified as digital technologies (Maghazei & Netland, 2017, p. 5). Being a special form of automated guided vehicles, UAVs have the same abilities. However, their environment is even more complex as UAVs move in a three-dimensional space, which requires more sensing skills and processing power.

Table 8: Filtering digital technologies related to manufacturing (own illustration)

#		TRL Group	Computing	Sensing	Memorizing	Communicating	Performing
1	Automated guided vehicles	III	●	●	●	●	●
2	Smart robotics	III	●	●	●	●	●
3	(Smart) collaborative robotics	III	●	●	●	●	●
4	Augmented reality	III	●	●	●	●	(●)
5	Track & trace	III	●	●	●	●	
6	Wearables	III	●	(●)	●	●	(●)
7	Mobile computing/devices	III	●	(●)	●	●	(●)
8	Sensors & Actuators	III		(●)	●	●	(●)
9	Virtual reality	III	●		●	●	
10	ERP	III	●		●	●	
11	MES	III	●		●	●	
12	Social media technology	III	●		●	●	
13	M2M	III	●		(●)	●	
14	Cloud computing	III	●		●		
15	RFID	III			●	●	
16	Artificial intelligence	II	●	(●)	●	●	
17	Machine learning	II	●	(●)	●	●	
18	Additive manufacturing	II	●		●	(●)	●
19	Big Data analytics	II	●		●		
20	Digital twin	II			●		
21	UAV/drones	I	●	●	●	●	●
22	Smart dust	I	●	(●)	●	(●)	(●)
23	4D printing	I	●		●	(●)	●
24	Blockchain	I	●		●		
25	Hologram	I	●		(●)		

Note: IoT, industrial automation, CPS, PLM, and digital/cyber security have been removed from the list due to their general character and as they are no technologies themselves.

Along with automated guided vehicles, smart robots as well as collaborative robotics belong to the group of digital technologies. Both possess all five attributes. First, smart and collaborative robots can collect internal information about attached tools and external information about changes of the environment. Collaborative robots recognize external parameter and objects. In case of an unforeseen event, these robots move away or stop operating to avoid any accidents. Also in everyday operations, smart and collaborative robotics can pick items, assemble and transport objects. Thus, performing ability is a fundamental basis for controlling its own state, manipulating the environment and operating autonomously. Moreover, smart robots can communicate with other systems and machines to coordinate their operations. For instance, they report their level of utilization or failures. Both systems require comprehensive computing power as well as a memory system.

In addition, AR solutions (i.e. in form of glasses) can be defined as a digital technology as they possess all relevant attributes. First, AR solutions have a sensing ability to gather external data from microphones, GPS or cameras (Azuma et al., 2001, p. 36). The resulting context awareness is crucial for their operability (Syberfeldt et al., 2016, p. 113). In combination with the computing ability, an AR solution can process data and communicate with external objects such as machines or the internet. For example, AR solutions recognize a defined product type and provide the maintenance instructions step by step. Data is stored either internally on the device or externally online. The latter is more typical for AR solutions, because of the limited frame size. Finally, AR solutions can indirectly perform actions by augmenting the operating space and providing real-time information to the operator.

Track & trace systems are no digital technology as such. However, they are a necessary module for building a digital technology. Track & trace systems can collect environmental information (i.e. location), process and communicate the location as well as, depending on the type, memorize the locations. The latter is fundamental for many technologies such as automated guided vehicles to develop motion patterns. Nonetheless, this technology is not able to perform any actions. Track & trace systems only provide information, which are needed for digital technologies to physically react and manipulate the surroundings (e.g. collaborative robotics, UAVs).

Depending on the type of wearables, this technology group can be considered as a digital technology. On the one hand, AR solutions typically have all the attributes of digital technologies and they are part of the group of wearables. Similarly, smart watches have a sensing, computing, memorizing, and communications ability. Further, they can indirectly change the environment by stimulating and instructing an operator. On the other hand, for instance, sensor shirts have less functionalities. Typically, they measure somatic functions and record the current status, but do not advise operators or perform any actions.

Similar, mobile devices at shop floor level have limited sensing and performing abilities. Subject to the system, mobile devices can use GPS, microphones or cameras to collect information. All mobile devices have in common that they have a computing and memorizing ability as well as communication skills. The same applies for M2M solutions. Usually, however, M2M focuses on the communication ability and other abilities depend on the type of M2M. Thus, M2M is also no digital technology in itself, but an important module enabling an integral system (e.g. smart robot) to communicate with other objects, humans or machines. As mentioned beforehand, sensors are important modules for integral systems such as automated guided vehicles or collaborative robots. Sensors record environmental parameters such as pressure, acoustic, light, temperature and, depending on the type, save the collected data. Actuators receive information from sensors and perform actions to change the parameters. In combination, both technologies are fundamental building blocks for other systems.

Comparing VR and AR solutions, VR has no sensing ability (Syberfeldt et al., 2016, p. 109). As this technology creates an almost realistic computer-formed three-dimensional world, which is independent from the actual real world, it does not require sensing abilities to collect real-time information from the real environment besides the input from the operator. Of course, a VR solution can animate a real setting, but the operator cannot receive external information. However, VR also needs computing, memorizing and communications abilities. In this case, it mainly communicates with the operator. Last, VR is not performing any actions in the real world, which means it does not manipulate the environment by physical actions.

ERP, MES and PLM systems are neither physical technologies nor digital technologies. Typically, these software solutions process and present data. The required data and information come from external sources such as machines, sensors, customers, etc. Thus, ERP and MES do not collect but process data. The results are valuable input for operators to make decisions or intervene in a process. Another attribute, memorizing, is important for ERP, MES and PLM to draw conclusions based on historical data and events. Although PLM is frequently discussed, it is not considered in this research, as PLM is more likely a management concept than a technology.

Equally, social media technology is grounded on digital structures, but it cannot be defined as a digital technology according to the relevant attributes. Social media technology processes and presents data, which comes from the users. It also memorizes data, which is stored in a closed loop platform or online.

Cloud computing and blockchain were developed to store information in one system. Both are frequently discussed in the context of digital technologies but are more supporting technologies for integral systems. Especially cloud computing is used by many companies to have data access anywhere at any time. Both systems store and analyze data, but do not collect it by themselves. They also do not perform actions in the real world. Thus, these technologies enable a centralized (cloud) or decentralized (blockchain) as well as secured data storage, which is important in the context of digitalization.

AI and machine learning can be evaluated as modules for more comprehensive systems. Depending on the solution, AI and machine learning collect information from outside based on speech analytics or pattern recognition. Typically, it requires sensors to gather this information. Hence, it cannot be determined as a digital technology in itself. The systems process information and communicate the outcomes either directly to operators or synchronize them with other systems. Finally, the memorizing ability is very important for AI and machine learning as recurring events are analyzed and the system learns from past events and its consequences.

RFID is a typical communication and information storage technology. Information is stored on a tag and read as well as (re)written by a reader. Hence, RFID is also a module or supporting system for machines or robots, but not a standalone digital technology.

Having a look at literature and on-going discussions about AM, 3D and 4D printing, it is unclear whether these technologies can be classified as digital technologies. From the perspective of the description model (chapter 3.1), AM technologies do not fulfil all attributes to categorize them as digital technologies. Basically, they have computing and memorizing power. AM technologies receive input data from computer systems in form of CAD files and other graphic data. Afterwards, this input is transferred to physical objects by performing corresponding actions. Therefore, it is obvious that AM, 3D and 4D printing are manipulating the environment by creating new objects. Depending on the type of AM solution, the machine is also able to communicate with other systems or control tools to produce an object.

Additionally, Big Data analytics is, just like AI and machine learning, a requirement for many machines to enable them to perform actions. With the help of Big Data analytics, systems can process and store data, which are finally used to draw conclusions and make decisions. However, Big Data analytics software itself is not designed to collect data and perform actions.

Depending on the solution, smart dust technologies can offer a wide range of abilities. It can comprise sensors, communication controller, memory, and actuators. Therefore, depending on the specific features, it belongs to the group of digital technologies.

Last, holograms and digital twins are virtual representations or copies of a physical and functional object. Both technologies are convenient for presenting information in different forms, but do not have communication, sensing or performing features.

3.3.4 Summary and implications

Based on the analysis, only eight out of 30 technologies can be considered as digital technologies. With reference to the funnel models, three main digital technologies have been identified for further research. The selection process was composed of three stages. First, a study conducted by the ITEM-HSG revealed the potential impact of different digital technologies on high-wage locations, plant roles and IMN configuration. Second, the maturity of different technologies was determined with the help of TRL. Subsequently, only mature technologies that are actually applied in industry were selected. Finally, based on a literature review, five essential attributes were identified in section 3.1 and assigned to the existing technologies. Interestingly, not more than a handful of technologies from literature can truly be regarded as a digital technology from a scientific point of view.

Based on this approach, smart robotics (including collaborative robotics), automated guided vehicles and augmented reality were selected for the subsequent discussions. These digital technologies fulfill most of the selection criteria and offer promising benefits for industrial companies. Chapter 3.4 will primarily concentrate on these pre-selected technologies, but will not strictly exclude other digital technologies. It should be noticed that this selection is not conclusive as the case studies (chapter 4) will show the importance of additional technologies (i.e. MES and AM), which have at least theoretically an impact on plant roles and IMNs. Further, it will become clear that autonomous guided vehicles only affect single sites and do not have a decisive impact across locations.

3.4 Propositions on the impact of digital technologies on plant roles

The following section focuses on the potential relations between digital technologies and plant roles. It serves as the basis for the empirical data collection in chapter 4 (Yin, 2009, p. 18). Thus, it is intended to develop preliminary and tentative propositions. For that purpose, the most topically relevant plant roles from literature are presented. However, it is not the intention of the author to develop a new plant role typology, but to work with and adapt an existing one.

3.4.1 Selection of plant roles

Because of the rising number of plant roles it is not possible to address all typologies in detail. Therefore, only three role typologies are selected. It is arguable that the selection of the following plant roles excludes other interesting typologies. However, the following selection criteria should justify the selection and provide an objective explanation:

a. The selected role typology should focus on an "original" typology. In this context, "original" means that only initial role typologies by the authors are considered and not their modifications as mentioned in chapter 2.5. These adaptations are usually applied for a specific context and less scientifically grounded compared to the "originals" (Kretschmer, 2008, p. 57).
b. Typologies with a distinct focus on a specific type of roles besides manufacturing are discarded. This includes among others Chiesa (1996), Daub (2009), Medcof (1997), Nobel & Birkinshaw (1998), or Papanastassiou & Pearce (2005), which are either focusing on service or R&D units. In fact, the research on R&D units merely considers product innovation activities and laboratory roles. As this is not part of the research, it will be not addressed.
c. The typologies need to fit to the theories of RBV and DCV. Thus, selected role typologies need to reflect the resources, competences and capabilities of sites. As digital technologies are a company's specific resources or assets, they create distinct capabilities of exploiting competitive advantage. Future development perspectives for the capabilities is another preferable factor.
d. Further, the selected typologies should at least consider the network dimensions *location* and *competences* (table 5). These dimensions are relevant in two respects. First, *location* is an important factor for sites and for discussions about roles of high-wage countries. Second, the *competence* dimension ensures the focus on the capabilities and resources needed for managing digital technologies. Other dimensions such as *level of autonomy or integration, knowledge flow,* or *product scope* are less important.
e. The academic reputation of the plant role typology is essential. From chapter 2.5 one can see that most plant roles are based on a few standard works. These plant roles have been empirically tested by different authors and applicability has been confirmed by qualitative or quantitative research. Further these typologies have been applied in subsequent studies, which gives them a high reputation in the scientific community.

Based on the selection criteria, the typologies of White & Poynter (1984), Bartlett & Ghoshal (1986) and Ferdows (1989, 1997b) have been selected for further research. Each will be introduced shortly and then elaborated in terms of compatibility with digital technologies (sub-RQ1). To enhance clarity, technologies are bundled according to the derived classifications (1) automation and manufacturing technology, (2) data analytics and ICT, (3) human-machine interfaces, and (4) embedded systems from chapter 3.2.2.

3.4.2 Subsidiary roles according to White & Poynter

In 1984, White & Poynter proposed a plant role typology based on their findings in the Canadian manufacturing sector. They developed three dimensions *market-, product-* and *value-added* scope to describe site specialization. As presented in figure 8, White & Poynter (1984) created two frameworks with different strategies for subsidiaries.

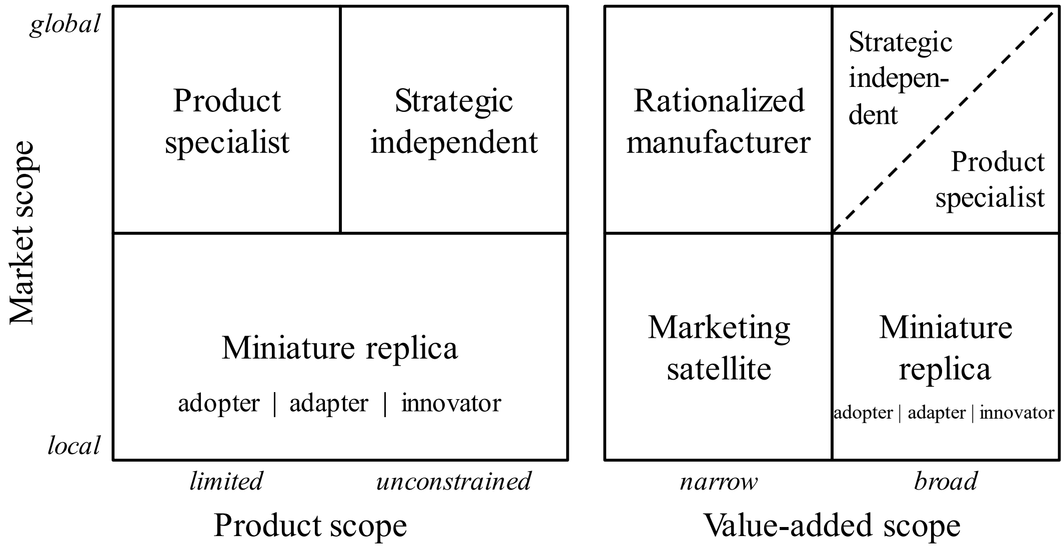


Figure 8: Role typology according to White & Poynter (1984, p. 60)

The *market* dimension describes the latitude of geographically distributed markets, which are provided by a plant, while the *product* scope is the range of new products or production line extensions of a site. The *value-added* scope depicts the extent to which a factory is carrying out value-adding activities in form of R&D, production, marketing, or after sales services (Hogenbirk & van Kranenburg, 2006, p. 55). The range of activities of a plant is highly dependent on the parent organization (i.e. headquarter), local and global competition as well as on the site's capabilities. Any changes in one of the three mentioned dimensions are accompanied by "a fundamental shift in the strategy" (White & Poynter, 1984, p. 59). The advantage of White & Poynter's (1984) typology is the comparatively high objectivity of the dimensions *market-, product-* and *value-added* in contrast to other dimensions such as knowledge flow (Daniel, 2010, p. 21).

The strategies for subsidiaries are divided into *marketing satellite, miniature replica, rationalized manufacturer, product specialist,* and *strategic independent*.

3.4.2.1 Marketing satellite

A *marketing satellite* has the lowest level of competences. Goods are neither produced nor innovations developed in a *satellite* site (White & Poynter, 1984, p. 61). Instead, it takes responsibility for customized sales, packaging or distribution (Delany, 2000, p. 226).

(1) Automation and manufacturing technology: A site without any manufacturing competence does not need automation and manufacturing technology for its business. It neither has the required know-how nor the processes to apply robotics, autonomous guided vehicles, etc. Thus, the value-added scope is narrow. In some circumstances, *marketing satellites* can make use of automation technology for packaging activities.

(2) Data analytics and ICT: The analysis and exploitation of customer and market data is more important for *marketing satellites*. Social media, AI or Big Data analytics can support existing screening methods to gather appropriate market information, which is needed for customized sales and market intelligence. Thus, *marketing satellites* are typically connected to a company-wide ERP.

(3) Human-machine interfaces: Like automation and manufacturing technologies, *marketing satellites* do not apply technologies such as AR or other wearables. However, they may use such solutions if systems, support or training is provided by other sites.

(4) Embedded systems: In fact, embedded systems have supporting functions for other systems such as automation and manufacturing technologies. As these technologies are not implemented, embedded systems are not essential for *marketing satellites*.

3.4.2.2 Miniature replica

This strategic plant role only exists in local markets. The plant produces goods of the parent organization and serves regional markets. It is a small replica of the larger scale parent company. According to the product and marketing scope, *miniature replica* are segmented further into adopters, adapters and innovators. In the first case, a plant simply takes on product lines and marketing initiatives from the parent organization. In contrast, an adapter makes modifications for local customer requirements. An innovator develops independent solutions for the regional market, which are usually an extension of the existing product portfolio. (White & Poynter, 1984, p. 60)

(1) Automation and manufacturing technology: Subject to region and the average labor cost of the market where a *miniature replica* site is located, both automation as well as

manufacturing technology have a potential impact on a site. On the one hand, automation technology (e.g. robotics, automated guided vehicles) have the potential to reduce direct labor cost. Depending on market conditions, this may have an enormous influence on the overall production cost. The *miniature replica* strategy is especially beneficial in markets with challenging customer requirements or to avoid trade barriers and high transportation costs. Thus, AM is a promising technology to address individual customer needs. As long as AM is not suitable for mass production due to quality and material cost issues (Strange & Zucchella, 2017, p. 178), it still can be used for rapid prototyping to accelerate time-to-market. The latter is pertinent for *miniature replicas* with innovator status.

(2) Data analytics and ICT: *Miniature replicas* require two kinds of data. First, they need internal data about technologies, processes and products. These can be gathered via MES, ERP and shared via cloud computing. As *miniature replica* sites produce goods, which are also produced on a larger scale at other sites, they can rely on the existing information. Second, *miniature replicas* are responsible for a specific region or market. Therefore, they need to acquire external customer and market data via social media or other market sources. Hence, data analytics and ICT have a high impact on *miniature replica* sites.

(3) Human-machine interfaces: Technologies such as AR or other wearables support decision-making at shop floor level. As the level of competences of a *miniature replica* site are limited, other plants can use AR to provide remote advice for troubleshooting or employee training. Likewise, VR or mobile devices support decision-making on the shop floor across sites.

(4) Embedded systems: Embedded systems are typically not implemented as standalone solutions. In particular, *miniature replica* sites receive all systems, modules and know-how from other plants. Hence, the impact of embedded systems is limited.

3.4.2.3 Rationalized manufacturer

Rationalized manufacturers produce a definite product line for global markets. However, their value-added activities are limited, as they do not perform any development or marketing tasks. The latter are typically managed centrally and supported by *marketing satellites* (White & Poynter, 1984, p. 61).

(1) Automation and manufacturing technology: Automation technology has the potential to reduce labor costs of *rationalized manufacturers*. In fact, this is exceedingly dependent on the specific product. Typically, only one product line is produced, so automation is possible. However, it also depends on the complexity of the manufacturing steps and the products. Automation in lower-cost countries might also be worthy of discussion.

(2) Data analytics and ICT: The impact of data analytics is restricted to internal data analytics. Less external data is processed as *rationalized manufacturers* do not perform any marketing activities. Nonetheless, *rationalized manufacturer* sites can derive benefits from MES systems to increase the transparency and efficiency of internal process steps. Machine learning would be a promising technology as well, but development capabilities are too low for such a resource-intensive technology.

(3) Human-machine interfaces: The impact of AR, other wearables or VR on this site role is comparable to the effects on *miniature replica* factories.

(4) Embedded systems: Embedded systems are typically not relevant for *rationalized manufacturers,* unless they are part of an integral system.

3.4.2.4 Product specialists

Product specialists have a high degree of autonomy. These plants develop, produce and sell definite products independently. However, they typically stay within the core business of the parent organization. Additionally, *product specialists* conduct independent marketing activities and are fully responsible for their products along the value chain (White & Poynter, 1984, p. 61). The exchange with the parent organization is rather limited.

(1) Automation and manufacturing technology: *Product specialists* have the required competences to implement digital technologies. First, automation technology can be used to reduce labor cost if a plant is located in high-wage environments. Depending on the final product, smart robotics or autonomous guided vehicles are supporting technologies. Second, *product specialists* can develop new solutions in the field of automation and manufacturing technology (e.g. AM). However, their contribution to the overall network is still limited. Successful implementations and practices are not shared with other sites in the network on a regular basis.

(2) Data analytics and ICT: Internal and external data sources are essential for the operations of a *product specialist*. Different systems such as AI, machine learning, social media, or Big Data analytics support the process of data collection, storing, processing, and exploitation. The connection to ERP and MES can further enhance existing structures.

(3) Human-machine interfaces: AR and other wearables can have an impact on shop floor operations at *product specialist* sites. These systems are either provided by other sites or developed and tested internally. VR has the potential to visualize products and processes before they are physically created. Thus, it likely reduces R&D costs and accelerates

innovation processes. Once again, the coordination across sites by utilizing human-machine interfaces is not intended by *product specialists*.

(4) Embedded systems: In this context, embedded systems can be important for *product specialists*, but not as standalone solutions. For example, track & trace is highly relevant for coordinating and controlling products as well as processes at *product specialist* sites. Moreover, *product specialists* have the competences and responsibilities to further develop embedded systems.

3.4.2.5 Strategic independent

A *strategic independent* plant has the highest level of autonomy. It makes decisions without consulting the parent organization and has resources to develop, produce and market new products (White & Poynter, 1984, p. 61). Also, the exchange with the parent organization is limited for *strategic independents*.

Although the product scope of *strategic independents* is broader in contrast to *product specialists*, the impact of (1) automation and manufacturing technology, (2) data analytics and ICT, (3) human-machine interfaces, and (4) embedded systems is comparable to *product specialists*. For most technologies, the impact is estimated to be high.

The following table 9 provides an overview of the findings.

Table 9: Digital technologies and plant role impact matrix I (own illustration)

		Digital technology classification			
		Automation and manufacturing technology	**Data analytics and ICT**	**Human-machine interfaces**	**Embedded systems**
Role typology according to White & Poynter (1984)	Marketing satellite	o	+	o	o
	Miniature replica	++	++	+	o
	Rationalized manufacturer	+	+	+	o
	Product specialist	++	++	++	+
	Strategic independent	++	++	++	+

Note: o :no impact + :low impact ++ :high impact

3.4.3 Role typology by Bartlett & Ghoshal

Bartlett & Ghoshal (1986, p. 88) criticize that “most multinationals treat their foreign subsidiaries in a remarkably uniform manner”. From their point of view, sites can adopt very different roles and strategic positions in an IMN. Thus, Bartlett & Ghoshal (1986) developed a matrix with the dimensions *strategic importance of the local environment* and *competence of local organization*. The local environment is determined by its size, competitors or technological advancements. Competences are defined in terms of production, technology or marketing activities. This dimension is closely linked to RBV.

The types of relationships or flow between the sites are classified into four categories: people, information, physical goods, and financial resources (Bartlett & Ghoshal, 1989, p. 48). Bartlett & Ghoshal (1986, p. 90) appreciate that their typology is "a somewhat oversimplified conceptualization of the criteria and roles, but it is true enough for discussion purposes". Additionally, their typology is rather conceptual driven than empirical (Kretschmer, 2008, p. 100). Figure 9 presents the final typology.

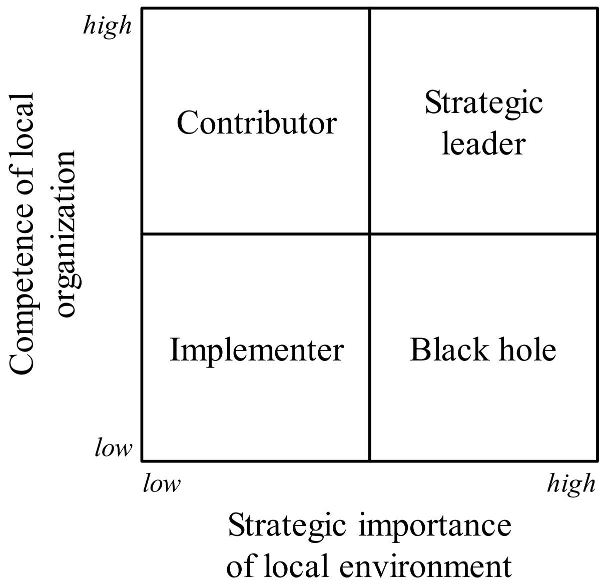


Figure 9: Role typology according to Bartlett & Ghoshal (1986, p. 90)

The resulting roles are defined by Bartlett & Ghoshal (1986) as follows:

3.4.3.1 Strategic leader

A subsidiary that operates in a strategically important market and is very competent regarding its responsibility area is called a *strategic leader*. Such a subsidiary is typically seen as a partner of the headquarter and analyzes changes and market dynamics (Bartlett & Ghoshal, 1986, p. 90). Hence, its degree of competences is the highest in terms of technology, production or marketing and it operates relatively independently from the headquarter (Schmid & Kutschker, 2003, p. 175).

(1) Automation and manufacturing technology: A *strategic leader* plant can profit from different perspectives on automation and manufacturing technology. On the one hand,

strategic leaders can increase the level of automation to reduce labor cost. Autonomous guided vehicles, collaborative or smart robotics are valid examples. Assuming that a strategic important market involves specific customer needs, AM technologies can further support the customization of products. On the other hand, *strategic leaders* are responsible for R&D and innovations across locations and therefore drive the development of automation and manufacturing technologies. Here, AM can support the prototyping processes. Besides, a *strategic leader* site also ramps-up and implements these technologies. The range of activities also includes technical support and training for other sites within the network.

(2) Data analytics and ICT: The analysis of external as well as internal data is crucial for *strategic leaders*. External market and customer data are especially relevant. *Strategic leaders* operate in their own market and must necessarily acquire their own data and market information. AI, social media or Big Data analysis can support the process of collecting, storing and processing data. Whereas ERP shares and distributes additional information from and to other sites, MES has the potential to increase internal transparency and efficiency in manufacturing processes. Therefore, both data analytic tools and ICT solutions have a big impact on the daily business of *strategic leader* sites.

(3) Human-machine interfaces: In fact, *strategic leader* sites have the highest level of competences. Thus, also human-machine interfaces have an impact on the operations. On the one hand, *strategic leaders* can make use of these technologies in manufacturing or marketing. For instance, AR can virtualize sales processes in direct interaction with customers as product features can be added to an object visually to increase customer experience. Supplementary, AR can be used to control and coordinate other locations. With the help of cameras and microphones integrated in AR solutions, experts at a *strategic leader* site are able to see and analyze the situation in other factories and provide guidance without being physically present. On the other hand, *strategic leaders* actively develop and test human-machine interfaces for other locations.

(4) Embedded systems: Embedded systems have a low impact on *strategic leaders*. Typically, technologies such as M2M, sensors, RFID, or actuators are no standalone solutions, but integrated in more complex systems such as robotics or autonomous guided vehicles. However, *strategic leaders* are responsible for developing and continuous improving embedded systems.

3.4.3.2 Contributor

A *contributor* has comparable competences to the *strategic leader*, but it is located in a strategically (rather) unimportant market. Companies often see a threat in this role, as their competences are much higher than needed. On the one hand, this could be a waste of capabilities or resources and, on the other hand, it may contradict the overall strategy (Bartlett & Ghoshal, 1986, p. 90).

(1) Automation and manufacturing technology: Like *strategic leaders*, *contributor* plants benefit in two ways from automation and manufacturing technology. First, they can automate existing processes to reduce labor cost. This can become even more relevant in strategic less important markets, because predominantly mass products are sold. Second, *contributors* have the ability to further develop such technologies. However, most companies tend to limit the responsibilities of contributors in R&D as well as their contribution to the overall network.

(2) Data analytics and ICT: In direct comparison to *strategic leaders*, data analytics is less relevant for *contributors*. Although these sites could develop machine learning, AI or cloud solutions, the execution is reserved for *strategic leaders*. Nonetheless, *contributors* can make use of ERP and MES systems.

(3) Human-machine interfaces: Technological solutions such as AR, VR or wearables are less relevant for *contributors*. Of course, these technologies may help to increase efficiency, but it is neither important for marketing nor for R&D activities.

(4) Embedded systems: Latest embedded system developments are important for *contributors*, but only as a module of an integral system. Thus, the impact of embedded systems is marginal.

3.4.3.3 Implementer

A subsidiary that neither operates in a strategically relevant market nor has a high degree of competences is defined as an *implementer*. They have just enough competences to operate in their local market and headquarter dependency is high. However, *implementers* are important for global businesses as they are generating value and income (Bartlett & Ghoshal, 1986, p. 91). Bartlett & Ghoshal (1986) emphasize that most national sites of any company are *implementers*.

(1) Automation and manufacturing technology: Depending on the location, automation and manufacturing technology can have a high impact on *implementer* sites. Especially for locations in high-wage countries, the higher degree of automation can reduce labor

cost significantly. In low-wage regions such automation solutions might improve product quality. *Implementers* receive all technologies and process know-how from *strategic leaders* or the headquarter. Therefore, they do not need to invest in development capacities. Hence, assuming that at least some *implementer* sites are positioned in high-wage environments, automation technology could have a high impact on this site role. Other technologies such as AM seem less important due to the low competences and the strategically rather unimportant markets.

(2) Data analytics and ICT: To exploit the advantages of AI or machine learning, a high degree of competences is required. Consequently, *implementers* do not make use of such technologies, unless they are provided, implemented and operated on site by the headquarter or *strategic leaders*. Similarly, MES and ERP are developed externally and *implementers* only apply these ICT solutions within given boundaries.

(3) Human-machine interfaces: The impact of human-machine interfaces on *implementer* sites is twofold. First, AR, VR or wearables have the potential to increase efficiency in operations and reduce the number of accidental misuses by guiding operators. Second, higher qualified sites can use, for example, AR technology to control and coordinate processes within an *implementer* site. Hence, human-machine interfaces have an indirect impact on the operations of *implementer* sites.

(4) Embedded systems: Compared to *contributor* sites, embedded systems have a marginal impact on *implementer* sites, too. All developments and new applications that belong to this technological class are developed by *strategic leaders* and *implementers* only apply "ready to use" technologies.

3.4.3.4 Black hole

A *black hole* site is located in a strategically important market but does not have an appropriate level of competences. These sites are essential for market access to screen market developments, technologies or competitors. However, *black holes* receive all resources and guidance from the headquarter (Bartlett & Ghoshal, 1986, p. 91).

(1) Automation and manufacturing technology: If a *black hole* does not produce any goods and only focuses on the collection of information and acquisition of know-how, both automation and manufacturing technology are not pertinent for this plant role. If it has more responsibilities, all implemented technologies must fit to the low competence requirements of *black holes*.

(2) Data analytics and ICT: For *black holes*, data analytics is highly important for collecting and processing external information. These sites rely on efficient analytic tools

to gather market information. Big Data analytics, cloud computing, social media, or AI are useful technologies for optimizing existing data operations. However, *black holes* need guidance, technical support and training from headquarter or *strategic leader* sites for all technologies they use.

(3) Human-machine interfaces: Typically, human-machine interfaces are less applicable for *black holes*. They apply such technologies only for marketing activities and need support from headquarter. Indirectly, *black holes* can be coordinated through AR or VR.

(4) Embedded systems: These systems have no impact on *black hole* sites except if they are integrated into integral systems such as robotic or AR.

Table 10 summarizes the findings of this section.

Table 10: Digital technologies and plant role impact matrix II (own illustration)

		Digital technology classification			
		Automation and manufacturing technology	**Data analytics and ICT**	**Human-machine interfaces**	**Embedded systems**
Role typology according to Bartlett & Ghoshal (1986)	Strategic leader	++	++	++	+
	Contributor	+	+	+	o
	Implementer	++	+	+	o
	Black hole	o	+	o	o

Note: o :no impact + :low impact ++ :high impact

3.4.4 The lead factory role typology by Ferdows

The most recognized typology was developed by Ferdows (1989, 1997b). His intention is the creation of a concept for an ideal design of IMNs and configuration of foreign production sites. From his point of view, the potentials of foreign manufacturing factories are often not sufficiently exploited due to unclear strategic roles or missing development perspectives. Companies that really understand the possible benefits of their foreign factories and evolve the competitive advantage are "rewarded in the form of higher market share and greater profits" (Ferdows, 1997b, p. 74).

With reference to Ferdows (1997b), a plant role has two dimensions (see figure 10). The first is the *primary strategic reason*, which can be delayered into *access to low-cost* *production, access to skills and knowledge,* and *proximity to market*[5]. *Low-cost production* factors comprise, apart from labor cost, cheap raw materials or energy cost. *Access to skills and knowledge* includes the proximity to qualified employees, research institutions, universities, or technology clusters. *Proximity to market* allows a plant "more rapid and more reliable product delivery, and facilitates the customization of the product according to customer requirements" (Vereecke & Van Dierdonck, 2002, p. 495). Other market factors such as overcoming trade barriers or local tax regulations also fall into this dimension.

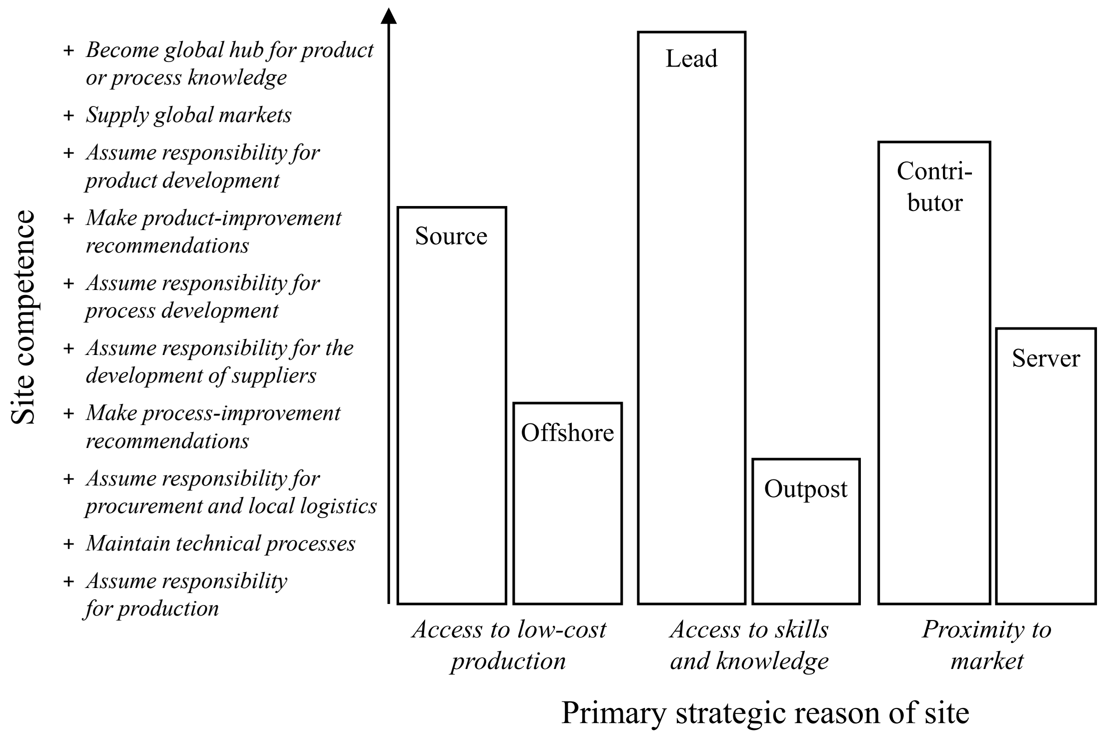


Figure 10: Plant role concept according to Ferdows (1989, 1997b)

The second motive for operating or establishing a factory is the level of *site competence*. This directly reflects the RBV. In total, ten site competences are listed along a continuum. At the lower end of the scale, sites have very limited competences and decision-making power. It ranges from the minimum, *assume responsibility for production* to the maximum, *become a global hub for product or process knowledge* (Ferdows, 1997b). Other researchers added competences such as technology choice, control system or performance measures (Vereecke et al., 2006, p. 1748) as well as production planning and scheduling (Meijboom & Vos, 2004, p. 129) to the site competences. The combination of

[5] *Ferdows (1989) mentions "control and amortization of technological assets" and "pre-emption of competition" as additional primary strategic reasons, but also emphasizes that these reasons are less prevailing.*

both dimensions results in a matrix (figure 10), which hosts six plant roles (Ferdows, 1997b, p. 76).

3.4.4.1 Offshore

The aim of an *offshore* factory is to produce components or products at minimum cost. The manufacturing process is less complex, and goods are typically exported, either for further processing or sale. Since the main purpose of such factories is access to low-cost advantages, managerial or development activities are reduced to a minimum and decision-making power is decentralized. (Ferdows, 1997b, p. 76)

(1) Automation and manufacturing technology: As the degree of competences of *offshore* sites is relatively low, they rely on the technology and process development expertise of other sites. However, automation technology is a key enabler for *offshore* sites to reduce cost. Once implemented, technologies such as robotics or automated guided vehicles can reduce direct labor cost. Additionally, gains in product and process quality are expected due to advanced automation. The savings can be especially significant for mass production goods. In spite of this, for example, AM offers only limited benefits for these sites as AM is still expensive from today's point of view (Strange & Zucchella, 2017, p. 178). These sites must cut cost continuously and hence will focus on automation and efficient manufacturing technologies – in particular if other plants take over the cost for development and capabilities for operating these technologies.

(2) Data analytics and ICT: Most data analytic technologies are rather expensive or less mature. Currently, *offshore* sites cannot derive benefits from these technologies. They receive new software and ICT solutions from other sites if they have proven to increase efficiency or reduce cost. Naturally, MES and ERP are also implemented in *offshore* plants to enhance steering and coordination.

(3) Human-machine interfaces: Most human-machine interfaces are inexpensive and therefore do not interfere with the low-cost attempts of *offshore* sites. Applications are conceivable for improving shop floor efficiency and for steering and coordinating this plant role from external sites.

(4) Embedded systems: In fact, embedded systems do not directly influence *offshore* plants.

3.4.4.2 Source

The strategic role of a *source* factory is low-cost production as it is for the *offshore* factory. In contrast, the management has broader responsibilities and abilities in procurement, logistics, production planning, and process optimization. Due to the fact that technically sophisticated goods can be produced, the requirements for the employees are just as high as in the high competence factories of the entire IMN. (Ferdows, 1997b, p. 76)

(1) Automation and manufacturing technology: As mentioned beforehand, automation technology potentially reduces labor cost. Depending on the quantity produced at a *source* site, the overall production cost can be reduced considerably and quality can be enhanced by implementing robotics. However, *source* plants are typically responsible for technically sophisticated products. Therefore, full automation is often not possible as processes are rather complex. Only most developed, smart or collaborative robotics can fulfil such tasks at present. This trade-off “automation versus product complexity” will be further discussed in the empirical study (see chapters 4 and 5).

(2) Data analytics and ICT: In contrast to *offshore* sites, data analytic software has a higher impact on processes in *source* locations. *Source* plants make product improvement recommendations and assume responsibility for process development. For both products and processes data analytics have the potential to change the existing structures significantly. For example, AI can improve product design and specifications as well as make process improvements (e.g. cycle time optimization). MES integrates information from quality, material or human resources management and influences process scheduling and control. In addition, knowledge can be stored and shared via cloud technology. Similar to *offshore* sites, ERP enhances steering and coordination. Von Krogh, Netland, & Wörter (2018, p. 54) augment “although off-the-shelf [ICT] solutions never guarantee that operations will improve, our findings show that increased use of data access systems leads to greater production cost reductions”, which is a desirable factor for *source* sites.

(3) Human-machine interfaces: Efficiency gains on the shop floor can be exploited by human-machine technologies. For a *source* factory with its strategic reason for low-cost production, AR, VR or wearables are important technologies with a high impact on production cost.

(4) Embedded systems: Latest embedded systems such as sensors, actuators or M2M are important for *source* factories, but only as part of an integral system. Therefore, the impact of embedded systems is rather low.

3.4.4.3 Server

A *server* factory supplies a specific region and has access to a national market. Its main purpose is to overcome foreign exchange fluctuations, customs, tariff and tax barriers, minimize transportation cost, etc. The autonomy of a *server* factory is higher compared to an *offshore* or *outpost* site to make adaptations and modifications for local customer demands. (Ferdows, 1997b, p. 76)

(1) Automation and manufacturing technology: As the strategic reason of a *server* plant is access to market, the benefits of automation technologies are limited for this plant role. Although costs, such as overcoming tariffs, foreign exchange fluctuations or tax barriers, are relevant for *server* sites, the focus is not on production costs, but on customization and fulfilling customer demands. However, automation technology such as robotic or autonomous guided vehicles potentially reduce production costs and either decrease the final product price or increase the margin.

More relevant are manufacturing technologies that support the customization of products. Especially AM has the potential to put individual product adaptations into practice. However, *server* factories receive most resources and know-how related to such digital technologies from a *lead* or *contributor* factory.

(2) Data analytics and ICT: Analysis of internal and external data is crucial for *server* factories. For example, AI or machine learning can use internal data to improve existing processes or products. Even more important is external customer information. Social media or Big Data market analytics are necessary to receive a sophisticated market and customer understanding, which will be used to customize the company's product portfolio according to customer requirements. A company-wide ERP and cloud solutions allow sharing of market information and analyzing upcoming trends from other regions.

(3) Human-machine interfaces: The application of AR or VR solutions offers interesting benefits for *server* plants. On the one hand, VR allows the simulation of whole processes or new products. Thus, new customized products can be visualized, and features tested without creating expensive prototypes. On the other hand, AR supports the production process by reducing preparation and working time.

(4) Embedded systems: The impact of embedded systems is limited for *server* plants. Besides internal benefits, these technologies have the potential to better interact with customers. This will be further discussed in the context of *contributor* factories.

3.4.4.4 Contributor

The strategic reason for a *contributor* factory is the proximity to market, much like a *server* site. There are, however, specific capacities and responsibilities for product and process development as well as supplier evaluation and selection. Due to the high level of competences, a *contributor* plant often competes with sites in the home country. (Ferdows, 1997b, p. 76)

(1) Automation and manufacturing technology: A *contributor* site can highly profit from digital technologies. On the one hand, automation reduces direct labor costs and potentially increases quality levels. On the other hand, AM technologies enable the production of customized products at minimal lot sizes. In an extreme case, each product can be produced individually for a customer. Such a customization improves customer loyalty (Kristianto, Gunasekaran, & Helo, 2017, p. 607). This is a crucial enabler for *contributor* factories, which follow a proximity to market strategy. In direct comparison, the purpose of a *contributor* site is not only to overcome tariff and tax barriers, but also to contribute to the overall manufacturing network. Mediavilla et al. (2014, p. 95) add that contributor sites typically have capacities for introducing new products or to make adaptations for local customers or exceptional occasions. Such a responsibility for product development and product improvements can be efficiently supported by AM technologies.

(2) Data analytics and ICT: Referring to *source* factories, data analytics and ICT have a similar impact on *contributor* plants. Data analysis of internal and external data creates further benefits due to the *contributor's* responsibility for product improvement, product and process development and other competences. The analyzed data directly function as input for product innovations and R&D processes. Finally, ERP or cloud computing can ensure a consequent distribution of information across locations.

(3) Human-machine interfaces: The benefits of human-machine interface technologies are similar to the ones of a *server* factory. Moreover, AR can also support a company-customer interaction. Even if the final, customized product does not exist, customers can see new features directly on a standard product with the help of AR. This technology has the potential to increase sales and positively impact customer's buying behavior.

(4) Embedded systems: These systems have only limited impact for the production environment of *contributor* sites. However, thinking outside the factory boundaries, track & trace of products or sensors that collect information about the product handling in the field can result in promising advantages. It enables a new form of tracking complaints and quality issues for guarantee claims, which are linked to a misuse of the specific product. Further it can be used for enhancing delivery reliability. Similarly, the tracking of products can result in new business models.

3.4.4.5 Outpost

This site is only responsible for a limited range of manufacturing tasks. The actual purpose is to collect information and acquire know-how. It is of little importance for the design of an IMN but supports other sites with market intelligence and information. Thus, an *outpost* factory is located in an area where advanced suppliers, research institutions, competitors, or customers are. (Ferdows, 1997b, p. 76)

(1) Automation and manufacturing technology: Automation and manufacturing technology has no impact on *outpost* factories. *Outpost* factories do not manufacture any products and therefore they neither need manufacturing nor automation technologies.

(2) Data analytics and ICT: Data analytic tools and ICT solutions are the only relevant technologies for *outpost* sites. To collect, store, process, and exploit external market data, various digital technologies can be used. Large amounts of market data can be processed by Big Data analytics methods and stored in the cloud or distributed with ERP. Other technologies such as MES or machine learning are less relevant for *outpost* sites, because they do not manufacture anything.

(3) Human-machine interfaces: Wearables and other human-machine interfaces are not relevant for *outpost* sites. In some circumstances, these digital technologies can be applied in other functions such as marketing or sales, but not in the manufacturing environment.

(4) Embedded systems: Just like automation, human-machine interfaces, manufacturing technology, and embedded systems have no impact on *outpost* sites.

3.4.4.6 Lead

A *lead* factory represents the highest level of competences. It is a kind of center of excellence (CoE) (Tykal, 2009, p. 59). A CoE typically entails three characteristics. First, it is a selected division of a plant or occasionally a whole plant, which owns specific knowledge and competences in an explicit field or for a process. Second, this knowledge is considered valuable for other sites and, third, a CoE controls and leverages knowledge sharing with other locations within the IMN "case-by-case" (Adenfelt & Lagerström, 2006, p. 395; Frost, Birkinshaw, & Ensign, 2002, p. 1000). Andersson & Forsgren (2000, p. 344) add that a CoE is commonly embedded and interacts with external stakeholders. In contrast to a CoE, a *lead* factory's competences and tasks are more comprehensive regarding product know-how, processes and technologies (Tykal, 2009, p. 87). For example, besides a knowledge hub function, a *lead* factory has innovation, market and manufacturing responsibilities for the entire company. The access to knowledge and skills is fundamental, as it is responsible for all kinds of innovations. Additionally, customers, advanced suppliers or research institutes are available in the immediate surrounding (Ferdows, 1997b, p. 76).

There can be several *lead* factories in one manufacturing network, which depends on the IMN size, products or markets (Blomqvist & Turkulainen, 2011, p. 9). For example, some companies operate a *lead* factory for less developed regions and for developed markets. Nonetheless, typically a *lead* factory is by definition not restricted to a regional market.

(1) Automation and manufacturing technology: The impact of automation and manufacturing technology on *lead* factories is extensive from different perspectives. First, automation technologies such as autonomous guided vehicles or smart robots have the potential to reduce direct labor costs. In many cases, a *lead* factory is located in a high-wage environment, which provides access to skills and know-how. Therefore, substantial labor cost savings are crucial for companies operating a *lead* factory in a high-wage country. Second, support technologies such as collaborative robotics can further reduce labor cost and support older employees on the shop floor as "demographics are fundamentally shaping the future workforce of production" (World Economic Forum, 2017, p. 16). Third, *lead* factories have the highest level of competences. Thus, *lead* factories are developing and implementing automation and manufacturing technology at the same time. They are also responsible for the effective roll-out to other sites in an IMN and continuous improvement. The R&D process can be enhanced by AM solutions in form of rapid prototyping.

(2) Data analytics and ICT: Data analytics and management is crucial for *lead* factories. They collect and process large amounts of internal process as well as external market data. In fact, if *lead* factories supply global markets, market data becomes even more important. Big Data analytics, AI or machine learning can improve existing structures and operations. In addition, *lead* factories sometimes are the host of the servers and central data management in an IMN. Therefore, they provide systems, technical training for employees and know-how. The ICT solutions as well as data analytic tools are also applied for an enhanced control and coordination of manufacturing sites within an IMN. In conclusion, data analytics and ICT have a high impact on the tasks and operability of *lead* factories.

(3) Human-machine interfaces: Likewise, human-machine interface technologies have a high impact on *lead* factories. On the one hand, AR, VR or wearables support older employees and simplify daily operations, which is becoming more important due to the different ageing structure in most high-wage regions. On the other hand, other sites can be guided and coordinated by using AR or VR technology.

(4) Embedded systems: Having the competence for product and process development as well as knowledge, a *lead* factory takes responsibilities for developing or continuous improving embedded systems. However, the impact of these technologies is not clearly assignable as RFID, M2M, sensors, etc. are typically modules of other integral systems.

The findings of the impact of digital technologies on Ferdows' (1989, 1997b) plant roles are summarized in table 11.

Table 11: Digital technologies and plant role impact matrix III (own illustration)

		Digital technology classification			
		Automation and manufacturing technology	**Data analytics and ICT**	**Human-machine interfaces**	**Embedded systems**
Role typology according to Ferdows (1989, 1997b)	Offshore	++	o	++	o
	Source	+	++	++	o
	Server	+	++	+	o
	Contributor	++	++	++	+
	Outpost	o	+	o	o
	Lead	++	++	++	+

Note: o :no impact + :low impact ++ :high impact

3.4.5 Further reflection of plant role elaboration

The discussions in the previous sections have shown that the characteristics and dimensions of the plant role typologies of White & Poynter (1984), Bartlett & Ghoshal (1986) and Ferdows (1989, 1997b) are comparable. For example, the roles *outpost* (Ferdows, 1989, 1997b)*, marketing satellite* (White & Poynter, 1984) as well as *black hole* (Bartlett & Ghoshal, 1986) show almost identical characteristics. In the same way, *lead* (Ferdows, 1989, 1997b), *strategic leader* (Bartlett & Ghoshal, 1986) and *strategic independent* (White & Poynter, 1984) sites have overlapping characteristics. Interestingly, all reviewed plant role typologies advocate a leading and strategically very important site that has a superior function in an IMN (cf. Enright & Subramanian, 2007, p. 914). Nonetheless, Ferdows' (1989, 1997b) typology is more specific and operationalized compared to the other role typologies.

The flaws of White & Poynter (1984) as well as Bartlett & Ghoshal (1986) are that their typologies are an oversimplification of the reality. Their dimensions only offer dichotomies and thus plants can either be the one or the other extreme (Enright & Subramanian, 2007, p. 920). Besides, White & Poynter (1984) do not consider any network exchange and contribution of sites to the overall network. In addition, Cavanagh & Freeman (2012, p. 603) highlight that "typologies based on dichotomous dimensions do not allow for [plants] to perform multiple roles simultaneously (as they dictate an "all or nothing" approach to each dimension)". This limitation has been overcome by Ferdows (1989, 1997b) as his typology considers a dynamic perspective of plant evolution (Meijboom & Vos, 2004, p. 129). Ferdows (1997b) proposes that a company can better exploit the full potential of its foreign production sites if they do not treat their plant roles as static entities but develop them according to an evolutionary path as shown in figure 11. On the one hand, plants need to continuously improve internal processes in terms of lean management, training, etc. to follow the evolutionary path. On the other hand, they need to develop new competences besides their daily business. To become a *lead* factory, plants need to take over "a global mandate" for a product or technology (Ferdows, 1997b, pp. 83–86). Hence, becoming a *lead* factory is a challenging and resource-intensive endeavor.

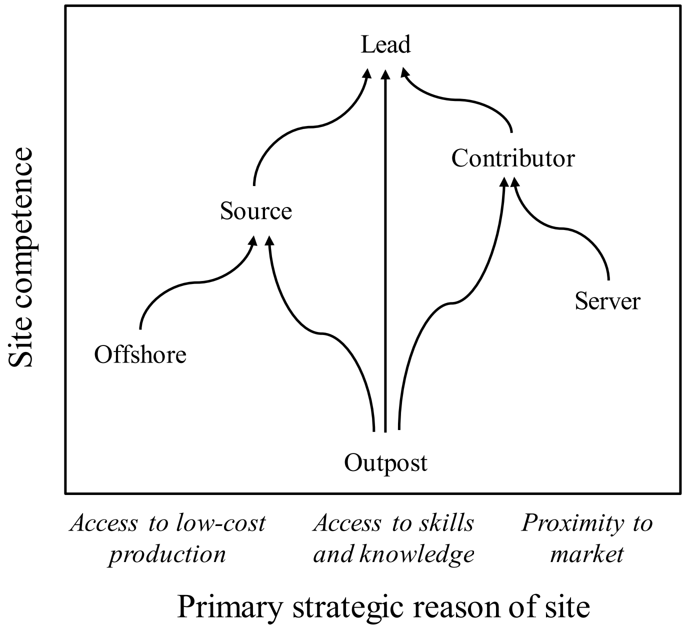


Figure 11: Plant evolution according to Ferdows (1997b, p. 79)

In contrast to the assumptions of White & Poynter (1984) or Bartlett & Ghoshal (1986), companies should not fixate on the existing roles of a given network. Instead, they should allow and actively support the development and upgrade of individual sites. This is a "natural evolution of plants in the direction of increasing site competence" (Meijboom & Vos, 2004, p. 129). Accordingly, Ferdows' (1997b) concept allows a dynamic analysis of individual, foreign production factories over time, which is the core argument of the DCV theory. Interestingly, Cheng et al. (2011) and Szwejczewski et al. (2016) found from their case studies that plants can also evolve in the opposite direction, for example, from *lead* factory to *contributor* or *server*. This might be explained by permanent outward transfers of knowledge, processes or products (Cheng et al., 2011, p. 1325). Furthermore, it must be noted that if all sites were to follow the evolutionary path, a production network would consist only of *lead* factories, which is probably not very practical. The unidirectional development in the *lead* factory direction would result in substantial risks and cannot be pursued indefinitely (Blomqvist et al., 2014, p. 66; Fusco & Spring, 2003, p. 33).

However, these facts as well as the circumstance that Ferdows (1989) was the first one to exclusively focus on manufacturing plants and companies (Cheng et al., 2015, p. 401; Mediavilla et al., 2014, p. 83), makes the *lead* factory typology most specific and applicable for further discussions. Additionally, Ferdows' (1989, 1997b) typology covers the main characteristics (e.g. competence dimension) and roles defined by White & Poynter (1984) and Bartlett & Ghoshal (1986). In direct comparison, it is even more specific and operationalized. For example, Mediavilla et al. (2014) developed clear guidelines for manufacturing companies to determine competences and roles of their sites. Ferdows' (1989, 1997b) typology is most recognized and the "most influential framework" (Demeter, 2017, p. 326), as it has been both empirically tested and applied in subsequent studies (Blomqvist & Turkulainen, 2011, p. 3; Blomqvist et al., 2014, p. 64). Therefore, it is most valid as Ferdows (1989, 1997b) addresses the specific needs of a manufacturing company's footprints. It has a high affinity to industrial practice, which will also be confirmed by the case companies in the next chapters. The empirical studies will reveal that Ferdows' (1989, 1997b) plant roles better represent the footprints of manufacturing companies as most roles have been applied in practice at least indirectly.

Another, less scientific reason to concentrate on Ferdows' (1989, 1997b) typology is the advantageous design and concept, which makes it very descriptive for managers and executives. Practitioners can easily position their sites in the framework and see the current state of their manufacturing network footprint (Meijboom & Vos, 2004, p. 129).

For these reasons, the typologies of White & Poynter (1984) and Bartlett & Ghoshal (1986) are not further considered in the empirical study.

3.4.6 Development of a plant-technology-competence framework

In a next step, the findings from chapter 3 should be combined. Hitherto, digital technologies and plant roles were discussed separately in this research as well as in literature. To overcome this issue, the following framework (figure 12) was developed to integrate both topics and facilitate the empirical research in the next chapters. According to Porter (1991, p. 98), "a framework […] encompasses many variables and seeks to capture much of the complexity of actual competition. Frameworks identify the relevant variables and the questions, which the user must answer in order to develop conclusions tailored to a particular industry and company".

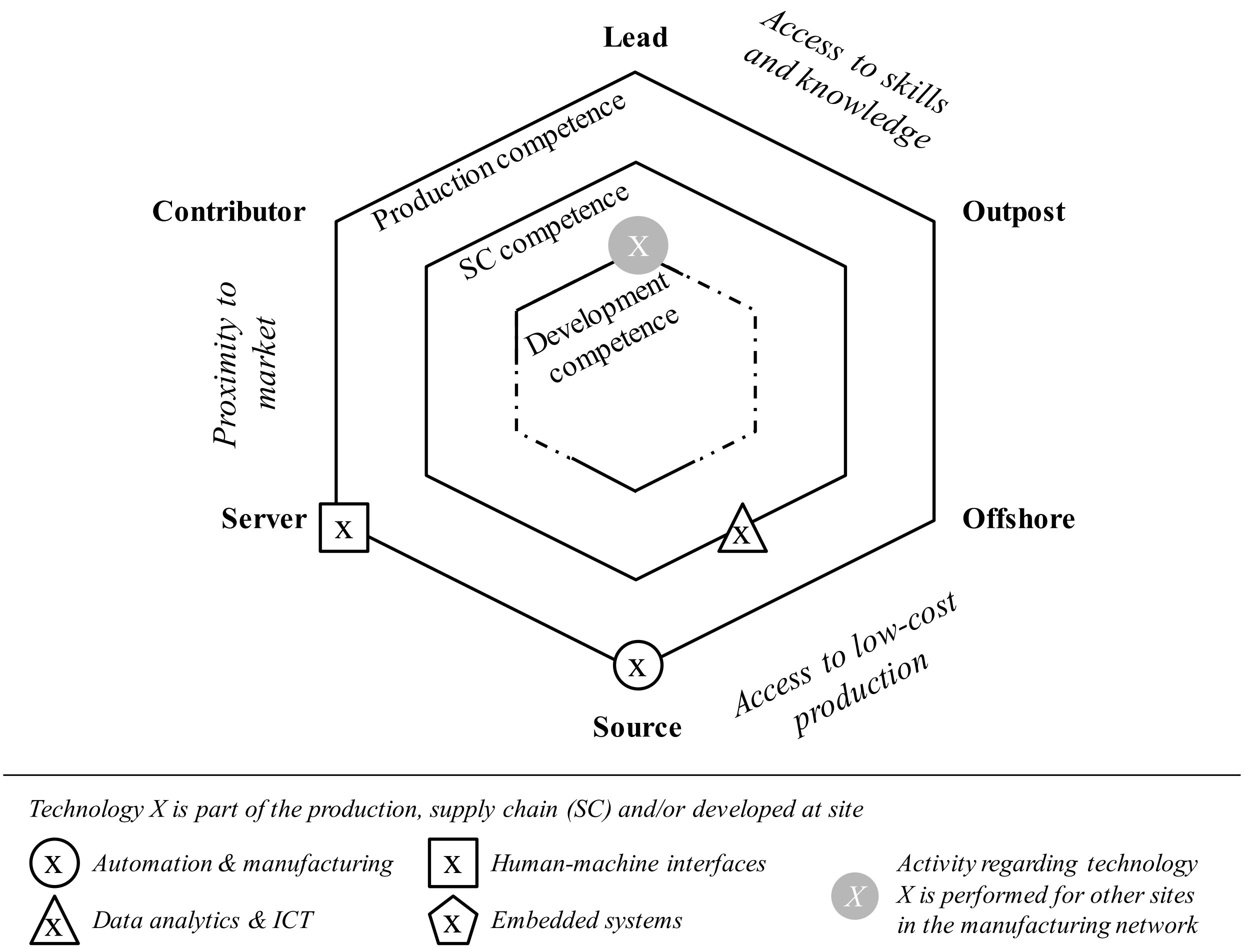


Figure 12: Plant-technology-competence framework (own illustration)

The framework is based on the main findings from literature. Ferdows' (1989, 1997b) plant role typology serves as the basic construct. The plant roles *offshore, source, server, contributor, outpost,* and *lead* are the starting point of the framework. Depending on the level of competence, the different hexagons represent production, supply chain and development competences. This is a compression of Ferdows' (1989, 1997b) site competences and based on Feldmann et al. (2013, p. 5698). Whereas production competence is the lowest degree, development skills refer to the highest level of competences. As described by Ferdows (1997b, p. 76) and Feldmann et al. (2013, p. 5698), production competence of a plant comprises the responsibility for production, technical maintenance and process-improvement recommendations. Second, supply chain responsibility includes procurement, local logistics, supplier development, and supply of global markets. Third, development competences combine responsibility for process and product development, introduction of new technologies, product-improvement recommendations, as well as serving as a global hub for product or process knowledge. Production competences are an important prerequisite for supply chain activities and both are relevant building blocks for development competences. Thus, the level of competences rises from the outside to the inside of the hexagon. As shown in chapter 3.4.4, each plant role has a specific range of competences. This is represented by the solid (competence existent) and broken lines (competence not existent).

Further, to integrate digital technologies, different symbols represent the technology classification according to chapter 3.2.2. These symbols illustrate the kind of technology by a specific number. The numbers can be obtained from table 8. For example, a square symbol with number 4 stands for human-machine interface AR. Similarly, other technologies can be added to the framework and assigned to production, supply chain or development competences of a site. A technology between two sites means that the technology is applied in both sites (e.g. triangle symbol). This should enhance readability in cases of larger networks or many technologies. However, for technologies that have been already rolled-out across all locations, the framework becomes unclear. Hence, it is advisable to focus on new technologies and the development competences. Last, the grey color shows that a specific technology activity is performed for other sites in an IMN. For instance, as shown in figure 12, the *lead* factory develops an automation or manufacturing technology also for other locations.

As this research seeks to support companies in managing their digital technologies more efficiently, the framework should help operation supervisors to manage their technological setup. This practical contribution is expected to be vital since most manufacturing companies are not aware of the potentials of digital technologies, their implementation and development status in the context of IMNs. Especially in the context of IMNs, Ferdows et al. (2016, p. 72) emphasize “the simpler the tool, the better. It seems that when faced with a complex problem, managers prefer simple tools as opposed to complicated ones”. However, the framework is only tested with two case companies, A and B, for several reasons. First, in some cases none of the interview partners was aware of the development activities of single plants. Second, not all case companies have definite plant roles. Although the framework is expected to work also without previous plant role determination, the activities in the corresponding case companies are less structured. Third, some companies operate large IMNs with more than 50 sites. In such cases, a table to structure the site portfolio would be more advisable to maintain clarity.

3.4.7 Summary and implications

The last sections discussed the potential impact of digital technologies on three selected plant role typologies (sub-RQ1). It became clear that the effect differs among technologies and no final or universal conclusion about the individual impact can be derived as the impact varies from company to company. However, the technology classification revealed that mainly automation and manufacturing technology, data analytics, ICT, and human-machine interfaces have an impact on various plant roles. In contrast, embedded systems do not directly influence manufacturing sites. The findings show that automation technology has the highest impact on high-wage locations or sites that are largely focusing on mass production. For plants having a strategic focus on access to markets, data analytics in form of social media, AI or Big Data analytics will become most relevant. These technologies can be utilized to collect, store, process, and exploit external and internal data. Besides, AM technology is promising for markets with dynamic customer demands as AM could realize the idea of producing customized products for individual customers. Moreover, it is evident that AR can be used for optimizing working conditions internally as well as externally to enhance customer experience. Finally, MES and ERP can support all kinds of site roles as these are promising technologies to enhance transparency and coordination mechanisms.

For leading sites, both the development and operation of digital technologies is rather important. Their high degree of competence in combination with their access to know-how and qualified employees allow leading factories to become global hubs for product and process knowledge and to become responsible for numerous support functions.

Finally, from the three discussed plant role typologies, Ferdows' (1989, 1997b) *lead* factory concept has been selected for further research due to several reasons mentioned in chapter 3.4.5. This typology is a key element of the developed plant-technology-competence framework and serves as the basis for the empirical case studies in the next chapter. The author is aware that "the plant role concept is complex to formulate, deploy and prioritize" (Mediavilla et al., 2014, p. 82). Further, Blomqvist et al. (2014, p. 67) question "whether the primary reason for the site can be identified at all in all situations, or whether multiple, equally important reasons for the site can be identified in some cases". However, after discussing digital technologies in combination with plant roles from a more scientific and theoretical perspective, the empirical studies should approve, refute, extend, or limit the findings from chapter 3. Therefore, the next chapters will examine supplementary coherencies and findings. The additional input from the empirical case studies should help to answer the underlying RQs more precisely.

4 Empirical studies

This chapter is dedicated to describing the empirical design and research methodology of the research project. After discussing the literature background as well as identifying and selecting appropriate digital technologies and plant roles, this section will seize the implications from chapter 3 and refine the outcomes. In chapter 4.1, the underlying research methodology will be introduced. Afterwards, chapter 4.2 to 4.4 describe the data collection of the applied case studies, while chapter 4.5 presents six within-case analyses. As an outlook, chapter 5 will demonstrate a cross-case analysis.

Some of the results in this chapter have been published in the subsequent publications:

- *Benninghaus, C., Budde, L., Friedli, T., & Hänggi, R. (2018), Implementation drivers for the digital industrial enterprise, in: International Journal of Production Economics, In review.*
- *Benninghaus, C., Elbe, C., Budde, L., & Friedli, T. (2018). Digital Technologies – Evolution of production in high-wage countries. Final report. Institute of Technology Management at the University of St.Gallen, St. Gallen.*
- *Benninghaus, C., Lützner, R., & Friedli, T. (2016). Industrie 4.0 – From a management perspective. Final report. Institute of Technology Management at the University of St.Gallen, St. Gallen.*

4.1 Case study methodology

The theoretical discussions and implications from literature serve as the basis for the empirical phase of this research. For the purpose of this research, qualitative research in the form of case studies seemed the most adequate research methodology. Eisenhardt (1989, p. 548) emphasizes that "case study research is most appropriate in the early stages of research on a topic". Thus, especially for fields with limited knowledge about coherencies and issues, the exploratory and inductive character of case study research offers rich and deep insights (Meredith, 1998, p. 444; Punch, 2005, p. 144; Voss et al., 2002, p. 197). Following the inductive approach, the idea is to derive generalizable patterns and regularities from individual observations (Tomczak, 1992, p. 77). While quantitative research is more useful for proving hypotheses in a large sample, case studies as part of "primarily qualitative research" focus on the generation, elaboration and testing of theories or models in small samples (Ellram, 1996, p. 97; Ketokivi & Choi, 2014, p. 233). For this research, theory generation and elaboration are the major reasons for conducting case studies. The main advantage of case study research is seen in the possibility of investigating phenomena in the real world (Eisenhardt & Graebner, 2007, p. 25) or a "natural setting that considers temporal and contextual aspects of the contemporary phenomenon under study, but without experimental controls or manipulations" (Meredith, 1998, p. 443). Yin (2009, p. 18) points out the advantage of case research that evolves "especially when the boundaries between phenomenon and context are not clearly evident". Additionally, Yin (2009, p. 9) proposes that case studies are most suitable to answer exploratory ("What?") or explanatory questions ("How?"). As the main RQ as well as the sub-RQs (table 1) are seeking for identification, description and explanation of theoretical and practical circumstances, the conduction of case research seems justified.

Apart from the mentioned parameters, this research follows the suggested procedure of Yin (2009). In contrast to Eisenhardt (1989), Yin (2009, p. 18) suggests a "prior development of theoretical propositions to guide data collection and analysis". These propositions can be found in chapter 3.4 as well as in the research framework (figure 2), which set the direction for the subsequent case studies.

4.2 Case selection

The case selection followed the principles of stratified purposeful sampling (Patton, 1990, p. 174) and the suggestions described in literature (Barratt, Choi, & Li, 2011; Creswell, 2007; Eisenhardt, 1989; Meredith, 1998; Stake, 1995; Yin, 2009). The idea is the selection of "information-rich cases" to derive major variations from cases to learn from (Patton, 1990, p. 169). Consequently, Eisenhardt (1989, p. 537) advises to select case companies not for statistical, but for theoretical reasons.

Initially, the research scope and boundaries were defined (Miles, Huberman, & Saldana, 2014). As a result, the research focuses exclusively on manufacturing organizations and does not consider other dimensions such as supply chain factors, marketing, human resources management, or technological features associated with digitalization. To select adequate case companies, the author developed an initial questionnaire with basic constructs to classify potential companies and to receive a first impression regarding potential case companies.

In contrast to single cases that are often used for longitudinal studies (Barratt et al., 2011, p. 331), multiple case studies allow a more comprehensive exploration of the research topic. Thus, a multiple case study approach leads to robust, in-depth insights as well as higher generalizability and empirical evidence compared to single case studies (Eisenhardt & Graebner, 2007, p. 27). While Eisenhardt (1989, p. 545) suggests four to ten case studies as a convenient quantity, Meredith (1998, p. 452) recommends between two and eight case studies. Following these recommendations, six within-case studies have been conducted to examine the unknown link between digital technologies and IMNs. Following

Eisenhardt's (1989) advice, the author stopped adding case studies after achieving theoretical saturation. In this context, "theoretical saturation is simply the point at which incremental learning is minimal because the researchers are observing phenomena seen before" (Eisenhardt, 1989, p. 545). Moreover, the author is convinced that the present case studies are sufficient to answer the RQs (Voss et al., 2002, p. 210).

The case companies stem from one or more of the following industry projects, which were performed at the ITEM-HSG between 2015 and 2018. Apart from two benchmarking projects with the focus on digitalization and high-wage locations, an additional public-founded CTI (Commission for Technology and Innovation) project was rolled-out to study the impact of digitalization on IMNs in more detail:

- Benchmarking "Industrie 4.0 – From a management perspective" (June 2015 – September 2016): The benchmarking project focused on the status-quo of digitalization approaches, technological developments, financial benefits, stakeholders, and change management. Out of 117 participants, five successful practice companies were selected by senior academics and industry experts (Benninghaus, Lützner, et al., 2016). Extensive on-site visits and workshops with an industry consortium supplemented the project.
- Benchmarking "Digital technologies – Evolution of production in high-wage countries" (December 2017 – November 2018): The focus of this benchmarking was on selected digital technologies and their impact on manufacturing sites and networks. AR, smart robotics, MES, and Big Data analytics were key elements of the project. Out of a sample of 139 manufacturing companies, five successful practice companies were identified that are leading in the application of the above-mentioned technologies from an organizational, operational and strategic perspective (Benninghaus, Elbe, et al., 2018). Several site visits and workshops complemented the project.
- CTI project with focus on manufacturing networks and high-wage production sites (November 2016 – April 2018): One case study is based on the outcomes of a CTI research project named "methodology for positioning high-wage manufacturing plants in global operations networks". Three Swiss manufacturing companies and one consultancy participated in the 18-month project. The aim of the CTI project was to develop a methodology that supports international manufacturers in positioning their high-wage manufacturing sites within their IMNs. The methodology also provided context specific configuration alternatives, which enable manufacturing sites to attain a competitive position and strengthen the

overall network performance. The development of a digital maturity model completed the project.

All selected case companies are headquartered in Central Europe, namely Germany and Switzerland, to enhance generalizability and comparability. Based on this geographical limitation, the case companies tend to have a higher organizational, cultural and social proximity just as a reduced political and economic distance (Ghemawat, 2001; Knoben & Oerlemans, 2006). For example, Maletzke (1996, p. 34) figured out that the more similarities two regions have, the lower is the cultural distance and vice versa.

4.3 Data collection

As mentioned, case companies were chosen from three projects. Especially, the group of high-performance companies from the benchmarking projects serve as a reference sample. The data represents managers' perceptions and consisted of questionnaires, semi-structured interviews, workshops, on-site observations, printed and qualitative data, and a focus group (appendix G). This procedure follows the principle of triangulation by combining and using manifold data sources to study a phenomenon (Eisenhardt & Graebner, 2007, p. 25; Voss et al., 2002, p. 206). This *data triangulation* improves the validity and substantiation of the cases (Eisenhardt, 1989, p. 538) and is eligible for case research (Eisenhardt, 1989, p. 534; Patton & Appelbaum, 2003, p. 60).

4.3.1 Questionnaires

All case companies filled out one or two online questionnaires, depending on the extent of participation in the benchmarking projects (appendix G). The following procedure was similar for both benchmarking projects. First, a survey was designed based on input from industry experts as well as a literature review. In this context, an industry expert is characterized by the fact that he/she has specific knowledge about structures, strategies and processes of the employing company, which is not accessible to everyone in the field of interest and therefore constitutes advanced knowledge (Meuser & Nagel, 2009, p. 467). Second, the questionnaire draft was revised by peer researchers and tested in the field with representative manufacturing companies. This feedback was used to review and sharpen the survey in multiple rounds. Third, adequate companies and business units were selected as survey participants by purposeful sampling. Fourth, both questionnaires (appendix H and I) were sent to manufacturing companies in Central Europe to identify relevant companies for the benchmarking projects and this research. For that purpose, the chosen companies were invited by email or phone and reminded after three weeks. Finally, 117 participants (benchmarking "Industrie 4.0") respectively 139 participants (benchmarking "digital technologies") returned a completed questionnaire. The questionnaire returns were reviewed and served as a pre-selection for the upcoming interviews. From this mixed sample, six case companies were identified as most suitable for further analyses in the case studies. This decision is based on different characteristics such as industry, management approach, implementation maturity, bandwidth of digital technologies, and IMN setup. The detailed selection criteria were defined by researchers and senior academics in various review sessions.

4.3.2 Semi-structured interviews

In-depth as well as *focused* interviews (Yin, 2009, p. 107) are central data sources for this research. Depending on the case company, interviews were conducted between January 2016 and July 2018. During that time span, large amounts of information were gathered, analyzed and interpreted.

In total, 24 interviews were conducted in German and English with an average of four interviews per case company (appendix G). The majority of interviews were done face-to-face. Only a few interviews with selected interviewees were conducted by telephone due to the time schedule of the interview partners. Although phone interviews are seen as more standardized, they lack the opportunity to recognize expressions, gestures and other evidences of the interviewee (Rosenthal & Rosnow, 2008, p. 171). However, both face-to-face and phone interviews were largely recorded and transcribed for further analysis (chapter 4.3.2.2). A small number of interview partners refused the audio recording. To make the results more convincing and to increase the likelihood of obtaining new findings, some interviews were conducted by a team of two researchers (Eisenhardt, 1989, p. 538). The different knowledge and insights of the observers opened up new perspectives and the resulting double-verification principle was used to confirm the findings. This approach to reduce the interpreter (i.e. systematic errors during interpretation of data) and observer's bias is known as *investigator triangulation* (Archibald, 2016, p. 228; Barratt et al., 2011, p. 331; Rosenthal & Rosnow, 2008, p. 128).

4.3.2.1 Interview specifications

The interviews took between 70 to 110 minutes. Each interview was done with one to three interview partners from different functions (e.g. strategy, manufacturing, technology, business development) and at different positions in the hierarchy (e.g. COO, global manufacturing manager, plant manager, project leader). Further, the interviewees had varying educational backgrounds and career histories with at least five years of professional experience in the field of IMNs. In order to reduce the potential perception gap between plants and headquarter, both organizational entities were addressed in many cases (appendix G). This approach is defined as *unit triangulation* (Marschan-Piekkari, Welch, Penttinen, & Tahvanainen, 2004, p. 254).

Before the interviews, a semi-structured interview guideline was developed (appendix J). A semi-structured interview approach is characterized by both structured and optional questions to facilitate and explore additional insights (Cachia & Millward, 2011, p. 268; Saunders et al., 2009, p. 320). Experienced researchers slightly adapted this guideline within the progress of data collection. The interview agenda, guideline and a slide deck comprising further information were sent to the interview partners before each interview. The transcripts were provided to the interviewees for feedback.

4.3.2.2 Qualitative content analysis and coding

Due to the vast amount of information from interviews, qualitative data, questionnaires, and observations, significant details had to be sorted from less pertinent information (McCutcheon & Meredith, 1993, p. 244). A common approach for analyzing large amounts of data is the qualitative content analysis. It is a method for the "interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns" (Hsieh & Shannon, 2005, p. 1278). More specifically, a conventional qualitative content analysis was applied as the knowledge base regarding the research phenomena is rather limited. Consequently, categories and codes were derived from the data sources instead from pre-existing categories, which is known as inductive development (Braun & Clarke, 2006, p. 83). The content analysis was guided by *thematic coding*, which "is a form of pattern recognition within the data, where emerging themes become the categories for analysis" (Fereday & Muir-Cochrane, 2006, p. 82). As a result, themes, categories, sub-categories, codes, and definitions were elaborated based on the interview transcripts (Bengtsson, 2016, p. 12; Creswell, 2007, p. 173; Hsieh & Shannon, 2005, p. 1279). For example, identified categories include, among others, strategic approach, technology, infrastructure, plant roles, or high-wage locations. Examples for codes within the technology category are technology portfolio, technology transfer and technology development. New codes and categories were systematically added to the initial coding frame. Hence, the overall idea of this coding process was to identify and analyze themes, patterns, similarities, relations, as well as divergences within the interviews (Braun & Clarke, 2006, p. 79). As this research is clearly structured (i.e. literature review, interview guideline), *thematic coding* is appropriate for the underlying study (Kuckartz, 2010, p. 91). All coding results were summarized in a mind map and reviewed category by category. The process was supported by the software ATLAS.ti 8.1.

4.3.3 Workshops and on-site visits (observations)

All case study companies participated in several workshops (appendix G). Depending on the project background, more or fewer workshops have been conducted (in total 37). On the one hand, in the case of the benchmarking projects, one to four employees from each case company participated in the workshops. For this purpose, each participant was invited to prepare a presentation and discussion round with lessons learned and successful practice implementations. The other representatives and researchers evaluated these approaches. Moreover, additional findings from other companies and literature were presented and discussed. On the other hand, in the context of the CTI project, six individual workshops were performed with a single case company. Manufacturing strategy, network configuration and coordination were discussed with regard to digitalization. A detailed core competence analysis and maturity evaluation of sites complemented the project.

Besides, as direct observations are crucial for complementing case studies (Meredith, 1998, p. 443), selected manufacturing sites of all case companies were visited at least once. During each on-site visit and plant tour, between two and eight company representatives were present in order to ensure *data triangulation* and to avoid single response bias (Patton, 1990). Both observations and personal impressions during the plant tours were documented to supplement the interview findings and provide a holistic case preparation.

4.3.4 Printed and qualitative data

To enhance the findings from the interviews and to create a more comprehensive picture of the case companies, additional printed and qualitative data were screened. These data included, among others, business plans, company presentations, white papers, marketing publications, annual and status reports, historical charts, financial statements, as well as confidential reports. The last two were received exclusively from the case companies and comprise information concerning production statistics, technology investments, production system, supplier evaluation, and organizational guidelines. The other data were either received directly from the interview partners, workshops or from public websites. Relevant information was incorporated into the case descriptions. However, the author did not apply any statistical methods to further analyze the content of the printed and qualitative data sources.

4.3.5 Focus group

From August 2017 to October 2018, the results of the case study research were discussed in a focus group. In general, the advantage of a focus group is that new insights can be gathered, which are triggered by the group interactions. Such a group constellation can stimulate the participants to contribute and mention aspects that would not come up in a single interview (Punch, 2005, p. 171). The focus group called "digital value creation" was established to promote exchange and sharing of practices across German and Swiss companies. These companies are well known in the media for their digitalization maturity and successful implementation of digital technologies. The participants were selected from different manufacturing industries to enhance generalizability and promote controversial perspectives. The focus group addressed executives, plant managers and project leaders. These company representatives were suitable partners for refining, evaluating and validating the findings. At each full-day focus group meeting 8 to 20 representatives from up to eleven companies participated.

For each focus group meeting a new guideline was developed and different methods have been applied. These comprise, among others, key notes, successful practice presentations, brainstorming, partner work, open discussions, or group work. Interim results were visible for all participants on a flip chart. Moreover, one or more researchers documented the discussions and results. After the focus group meetings, the findings of this research were revised based on the participants' feedback.

4.4 Reliability and validity in case study research

Although qualitative research may "have a very high impact" and provide much richer information (Voss et al., 2002, p. 195), it is an object of criticism. The main issue is the limited sample size, which is expected to limit the *reliability* and *validity* of the contributions. *Reliability* is defined as the extent to which the content and results of a case study could be repeated in other settings and at different times (McCutcheon & Meredith, 1993, p. 246; Yin, 2009, p. 40). Obviously, *reliability* is a concern of case research because of the limited sample size. Nonetheless, different approaches can reduce the impact. On the one hand, multiple data sources for each case ensure a better *reliability* (*data triangulation*). This also includes interviewing different stakeholders at each case company (Voss et al., 2002, p. 205). On the other hand, conducting case studies with more than one observer (*investigator triangulation*) limits the biased representation of findings (McCutcheon & Meredith, 1993, p. 246). In addition, the level of detail of the cases and an accurate documentation enhance the representativeness (Patton & Appelbaum, 2003, p. 66; Voss et al., 2002, p. 211).

Validity can be distinguished into *construct, internal* and *external validity* (Yin, 2009, p. 40). *Construct validity* originates from the ability to set operational measures by using multiple data sources. Hence, *construct validity* should ensure consistency between the construct and related factors (McCutcheon & Meredith, 1993, p. 245). *Internal validity* comprises the relationships between different factors and establishes a correct causal relationship and analysis of cause-and-effect relations (Yin, 2009, p. 40). In particular *data triangulation* can improve *internal validity* in case research (McCutcheon & Meredith, 1993, p. 246). *External validity* addresses the generalizability of the case findings. This is one of the most common criticisms regarding case research. However, to enhance *external validity*, Voss et al. (2002, p. 211) recommend conducting multiple case studies and Yin (2009, p. 54) suggests considering a replication logic (cf. literal replication and theoretical replication).

In summary, case study research requires triangulation, detailed observations, sophisticated interpretation, and analysis of cause-and-effect relations to assure *reliability* and *validity* (Meredith, 1998, p. 453). Thus, if performed correctly, case research is a valid approach in developing theoretical constructs or models that could be tested in a second step on a larger scale by using quantitative tools (Hitt et al., 2016, p. 83).

4.5 Data analysis and discussion

As discussed in the previous section, case research is an adequate research methodology for this research. First, little knowledge about the field and phenomenon of digital technologies in IMNs exists. Although both research areas are not completely novel, the link between both fields has not been addressed in theory and practice. Thus, hypothesis generation is not possible for quantitative research. Second, the topic can be investigated in-depth in its natural setting and, third, case studies are most adequate for answering exploratory and explanatory questions.

The case research follows the recommendations of Eisenhardt (1989) for a two-step approach. At first, the data within the individual case studies is analyzed (chapter 4.5). In a second step (chapter 5), cross-case patterns and conclusions are identified as well as implications derived (Yin, 2009, p. 57).

4.5.1 Case description and within-case analysis

In the first stage, each of the following case studies is treated and discussed separately as an embedded company case. The aim of this step is to give a detailed description and to derive distinctive insights (Barratt et al., 2011, p. 331). The cases vary in depth and length according to the company's specific contexts. The selected case companies represent multiple industries such as automotive supply, building, automation solutions, machine tools, home appliances, and electronics (table 12). Neither of the companies cooperate with each other nor do they compete in the market. The company names have been substituted by descriptive monikers. All cases show similar as well as differentiating characteristics. For instance, common elements are:

- Manufacturing industry
- At least four international manufacturing locations
- Minimum one site in a high-wage location
- Application of digital technologies (especially robotics and AR) as well as other technologies such as M2M, MES or Big Data analytics

Accordingly, all case companies are manufacturing business-to-business (B2B) and/or business-to-customer (B2C) goods. In addition, all of them have at minimum four manufacturing sites as "the rationale being that with three plants or less, companies have few opportunities for differentiating the role and focus of their plants" (Vereecke et al., 2006, p. 1740). Moreover, the focus on international sites should reveal differences across sites between geographical regions such as Asia or Europe. For answering sub-RQ3 satisfactorily, the author added the idea of operating at least one plant in a high-wage location. Last, all case companies have implemented a wide range of digital technologies and especially the ones mentioned above.

Table 12: Case overview (own illustration)

	Machine tool company (MTC)	**Building equipment company (BEC)**	**Automotive supply company (ASC)**	**Control & automation company (CAC)**	**Electronic equipment company (EEC)**	**Home appliances company (HAC)**
Scope of case	Business unit	Business unit	Business unit	Company	Company	Company
Market	B2B	B2B & B2C	B2B	B2B	B2B	B2C
Employees	>3,000	>25,000	>85,000	>20,000	>35,000	>15,000
Number of manufacturing sites	9	9	52	10	18	12
Revenue development (2014-2017)	+10%	+17%	+59% *	+27%	+63%	+22%
Manufacturing regions	Europe, Asia, North America	Europe, Asia, North America	Europe, Asia, Americas	Europe, Asia, Americas	Europe, Asia, Americas	Europe, Asia

** total company (no available figures for business unit)*

Finally, even though the case companies indicate common elements, Eisenhardt's (1989, p. 537) "polar types" suggestion is moderately considered. As shown in table 12, the cases are dissimilar in several criteria and cover a large range of polarizing characteristics (e.g.

application of technologies, degree of automation). Such intense cases can enlighten about successful practices and major failures of case companies (Patton, 1990, p. 169).

The case description focuses on (1) general information, (2) strategy and digitalization approach, (3) technology portfolio and implementation, (4) manufacturing network and site roles, and (5) high-wage location(s). A box with major implications summarizes each case study. Furthermore, the plant-technology-competence framework (figure 12) is tested with the case companies A and B to identify the implementation and development status of digital technologies in the context of IMNs. The reasons why the framework is only tested with two case companies were discussed in chapter 3.4.6 (and at the end of case B).

4.5.2 Case A: Machine tool company

The machine tool company (MTC) is one of three business units of a global corporation. Both corporate and business unit headquarters are in Switzerland. MTC produces tooling systems in the field of milling and electrical discharge machines, laser, AM, automation, tooling, and equipment. This broad product portfolio makes the business unit one of the leading global providers for the tool- and mold-making industry as well as for manufacturers of precision components. Approximately 3,000 employees work in nine manufacturing plants and R&D centers in Switzerland, China, Sweden, and North America. In addition, MTC is currently building a new factory in Switzerland, investing more than 80 million Swiss Francs. Moreover, MTC operates its own sales network in more than 50 countries to provide customer services locally. The most important customer segments are the automotive and aerospace sector. Between 2014 and 2017 MTC's revenue developed by +10 percent.

Concerning digitalization, MTC focuses on making their products smarter to derive benefits for its customers. Today, approximately 20 percent of MTC's products are connected via a virtual platform. However, according to the head of technical units, internal digitalization is seen as a "mandatory and important driver to keep manufacturing on a competitive level in high-wage locations".

4.5.2.1 Strategy and digitalization approach

MTC has positioned itself as a premium and high-quality provider. As a result, MTC offers its premium products worldwide and accepts the fact of being more expensive and having a lower sales volume compared to its competitors. In recent years, the product segments milling and laser systems were growing fastest followed by electrical discharge machines. In direct comparison, MTC had the highest innovation and technology output compared to its competitors. The business unit also has a well-known brand perception.

The main purpose of MTC's digitalization activities is to make use of data for internal and external processes. Thus, the intention is to "share correct and updated information" with the overall organization. For example, knowing in advance that one product has a potential delay, helps the workers to implement timely measures to avoid financial penalties. For its customers, MTC provides different solutions based on the availability of data. On the one hand, customers have access to the order status and can make subsequent feature changes even after production has started. On the other hand, various customer services are offered such as performance benchmarking, OEE (overall equipment effectiveness) control, remote diagnosis, or predictive maintenance. To further drive external digitalization activities, MTC acquired a leading software firm based in Germany to unlock new service potentials. This attempt underlines the strategic decision of becoming a full-solution provider as especially the customer segments automotive and aerospace demand full operational availability of the machines and a 24/7 support in form of service, spare parts delivery and maintenance.

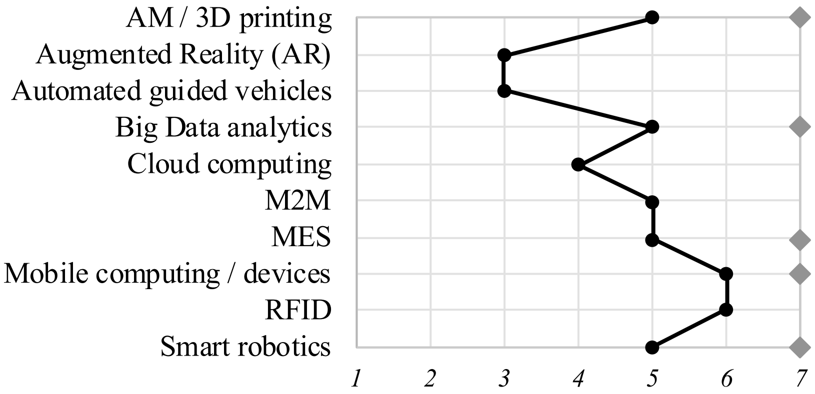
MTC has created a specific department for its digitalization activities. The department oversees new technologies that can be used in all plants. For specific machines and solutions, *lead* factories have a decentralized responsibility. The head of the department is reporting to the CEO. He supports digitalization activities not only at operational level, but also at strategic and customer levels. This setting facilitates a holistic and objective approach to digitalization with an interdisciplinary view. Furthermore, the business unit cooperates with suppliers and research institutes. In form of joint or commissioned research, both stakeholders serve as development cooperation partners by providing prototypes or single solutions for MTC.

4.5.2.2 Technology portfolio and implementation

Digital technologies are employed to increase production efficiency at MTC. Especially, RFID and mobile device technologies are used at the different sites. Figure 13 outlines the most dominating technologies according to the COO and head of digital transformation.

All products for the B2B market are produced according to the make-to-order principle. Thus, in this project driven business, automation plays a subordinate role. At present, automated guided vehicles and other automation technologies are less integrated as the product diversity is relatively high. Neither for small volume nor for complex products, has MTC strived for automation. An exception is the location in Sweden, where MTC has integrated smart robots to support milling and turning processes. In a next step they will try to achieve a certain level of automation in grinding. However, for automated grinding a kind of AI is required due to different applications, materials and surface conditions.

Therefore, the overall degree of automation at MTC can be estimated at around 25 percent. Only the electronics production in Switzerland is highly automated. Hence, automation and robotic density is linked to product types rather than locations, although electronics are exclusively produced in Switzerland. Additionally, a few years ago, the business unit acquired a leading AM providing company to extend its own product portfolio. Nowadays, several polymer and metal AM solutions are used internally for prototyping, spare parts and first small batch series production.



(1: implementation failed / 2: observing / 3: researching and developing / 4: working on the implementation (prototyping) / 5: already in first use / 6: fully implemented / 7: impact on manufacturing network and/or plant role(s))

Figure 13: Technology portfolio and maturity (case A) (own illustration)

The connectivity levels are much higher as almost 70 percent of the machines are connected. Connectivity is here defined as the ability of machines to communicate and exchange data with other machines or systems. The use of mobile devices and RFID in production and assembly processes fosters connectivity and real-time access to data. For example, an intermediate product, which is equipped with an RFID tag, is scanned (automatically) and the information is transferred to a central ERP system after each assembly step. All relevant stakeholders, such as sales specialists or those responsible for production, have real-time access to the stored data that show current assembly status, estimated delivery date, quality issues, and others. This software was developed internally and serves as a dashboard for the head of production. Failures, delays or other unplanned events are monitored, analyzed and reported in real-time. These systems are standardized and applied by all sites in the IMN. Thus, Big Data analytics has an enormous effect on internal production and productivity. Similarly, MTC implemented MES and cloud computing in the *lead* sites in Switzerland. Especially, the large-scale cloud system is estimated to have a "revolutionizing impact" on manufacturing and assembly principles.

Data is also used for AR solutions. AR is partly implemented for the training of new operators. By wearing smart glasses, workers receive guidance and can interactively learn production steps or navigate through the factory. In the future, AR is expected to support MTC's customers by providing instructions or other information.

By applying a bundle of technologies MTC was able to reduce costs by improving productivity, enhancing delivery dependability and product quality as well as increasing product and process innovations. In the future, the business unit will focus on smart and collaborative robotics, MES, cloud computing and Big Data applications (see figure 13). Although the processes of MTC are difficult to automate, robotics are expected to slowly complement or replace the human workforce. While these implementations are limited to MTC's high-wage plants, MES, cloud and Big Data solutions improve the coordination across sites and unlock new cooperation potentials within the IMN.

4.5.2.3 Manufacturing network and site roles

With five manufacturing sites in Switzerland, MTC has a strong Swiss footprint. Two other sites are in China, one in Sweden and one in North America. All factories have a relatively low production depth. The Swiss plants primarily focus on R&D, assembly and testing activities. MTC establishes ideas, pilots and projects in Switzerland. Hence, Asia can be seen as "a copy-paste" of activities and developments done in Switzerland first. Moreover, one Swiss *lead* factory is exclusively responsible for the electronics production for all machines worldwide, which is related to the process complexity. According to the COO, the business unit does this not for cost reasons, but to concentrate know-how as electronics are classified as strategic components for all their products. Whereas the Swiss factories focus on standard and high-end goods, Chinese sites are the factories dedicated to entry and standard products within the same product category and mainly serve Asian markets. Due to MTC's broad product portfolio, the exploitation of synergies between plants is limited. Although technologies are more linked to product types, level of automation tends to be higher in high-wage locations. Within the product group and the sub-network, the factories are similar and comparable for the same product.

The following types of plants are operated by MTC. These roles are explicitly communicated and systematic guidelines comprising rules and processes were used to create the existing manufacturing footprint.

- *Lead*: MTC's *lead* factories are related to specific products. For example, while one Swiss *lead* factory is responsible for electrical discharge machines, the other *lead* site produces milling products. They are responsible for R&D, production engineering, support functions, troubleshooting, and IT infrastructure. Decisions regarding manufacturing technology, product allocation or make-or-buy are also conducted by the *lead* factories. For instance, each factory must implement the same cutting machine as the *lead* factory for standardization reasons. Individual plants are not allowed to take such a decision. Thus, the *lead* factories fulfil all related tasks for their specific product portfolios and are responsible for the associated plants in their sub-network. Even though there are only a few similarities across product types, the production processes and technologies in a sub-network are mostly the same.

- Associated plants: Each *lead* factory, except for the *lead* factory in Sweden, has numerous associated plants, which manufacture components for a *lead* factory or standard respectively entry products of the same type. For example, the site Asia I produces electrical discharge machines and is guided by the *lead* factory Switzerland I (figure 14). Thus, associated plants have only limited competences and are comparable to *server* plants. However, even though the plants in Asia were set up as low-cost sites, they are now classified as *server* factories due to their important access to local customers. Hence, the primary strategic reason changed and therefore their site role. Apart from that, the business unit wants to bypass market protectionism by producing similar products in different locations.
- *Contributor*: The North American plant and one site in Switzerland (Switzerland V) have competences comparable to a *contributor* site. In fact, they are responsible for a key component for milling machines and therefore assume responsibilities for product development or product-improvement recommendations. However, they receive technologies and guidelines from the *lead* site Switzerland II.

Operational sourcing (e.g. order placement or small parts contracting), local supplier development, short-term capacity and manufacturing planning are the only responsibility areas that all sites can decide individually.

The subsequent figure 14 summarizes the technology competences of different plants. Only the technologies considered most important by the COO are presented. While mobile devices (7) and RFID (15) are used in all locations for different processes, the application of smart robotics (2) is limited to selected sites. The plants in Sweden and Switzerland I develop specific robotic solutions (2) just for their own production and supply chain processes. In contrast, the *lead* factory Switzerland II develops these solutions for other sites. Similarly, collaborative robotic (3) is developed for other locations. At present, MES (11) and cloud computing (14) are used in manufacturing processes in Swiss *lead* factories. Further, Big Data solutions (19) are implemented across sites for supply chain or production activities. After developing the software internally in Switzerland, it is rolled-out to Asian and other Swiss locations. Moreover, AM (18) is developed by an acquired firm and used for small batch or spare part production in different Swiss plants.

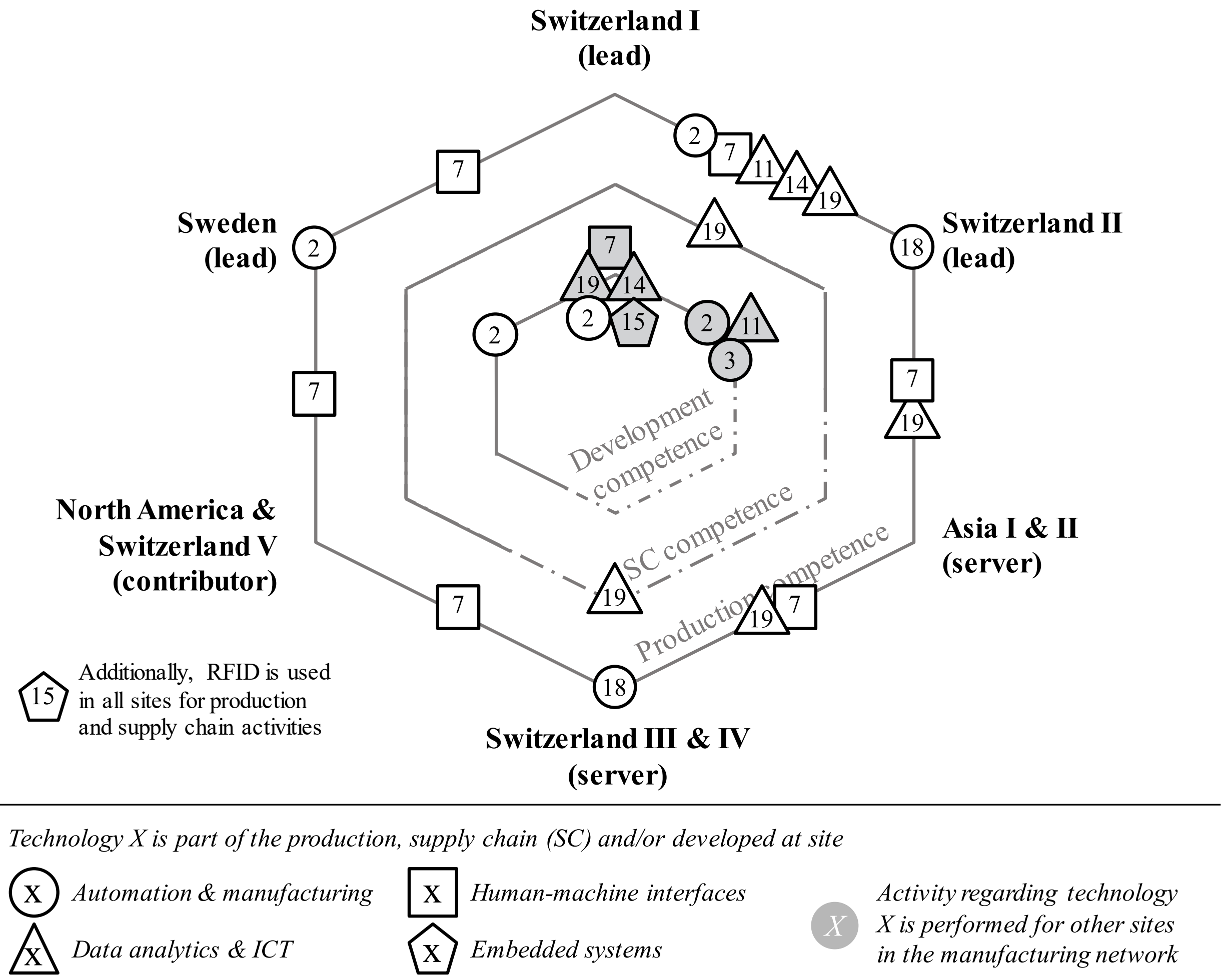


Figure 14: Plant-technology competence framework of case A (own illustration)

Although MTC's main purpose for implementing digital technologies is driven by data, the business unit works on several other applications. Especially, cloud computing (14) was considered as having a substantial impact. However, MTC's plant-technology-competence framework reveals that this solution is only implemented in the Swiss *lead* factories. In fact, this finding was rather surprising for the COO. Even though cloud computing should have been rolled-out to other locations, the application of this technology is limited to a few sites. In contrast, other technologies are used in more locations than planned. For example, smart robotics solutions (2) were implemented in the Swedish location and the electronics production at Switzerland I, but nowadays it is also utilized in Switzerland II. This development has been positively received, as smart robotics can help to automate different processes in high-wage countries. In a next step, the other

Swiss sites as well as the North American plant should make use of smart robotics. Hence, the plant-technology-competence framework helps and encourages to map the status quo and may visualize future developments. But it also provides support for identifying redundancies and undesired actions in MTC's IMN. Whereas the site roles and network structure were systematically designed and communicated, the responsibilities regarding digital technologies seem less structured. Besides the fact that MTC was initially focusing on data solutions and is now implementing a wide range of digital technologies, the framework discloses several unplanned and on-going development activities. Smart robotics (2) are developed in the *lead* factories in Sweden, Switzerland I and II. These redundancies result in extra cost and resource consumption. The COO was not aware of these development activities and convinced that only one *lead* factory takes responsibility for developing smart robotics. In the future, only Switzerland II should concentrate on smart robotic solutions and the development activities in Sweden and Switzerland I will be restricted. From this point of view, the plant-technology-competence framework has made a real contribution to the optimization of activities in MTC's IMN.

Additionally, figure 14 shows that different technologies have the potential to impact various plant roles. For example, AM is employed by both *lead* and *server* factories. Selected *server* factories can make use of AM for small batch production to serve individual customer needs. Although the level of competences of *server* factories is lower compared to *contributor* sites, the proximity to markets and customers is vital. Additionally, RFID and mobile devices support automation processes. Most new technologies extend the competences of plant roles, which mostly applies to *lead* sites.

Besides the existing footprint, MTC builds a new plant in Switzerland. As MTC's market is growing, the business unit needed to expand its existing footprint. The new plant will be the new *lead* factory for milling goods, concentrating all products, know-how and technologies. It is also equipped with the latest technologies. Thus, the use of digital technologies has a direct influence on the physical network footprint. The decision to build a new plant in Switzerland was clear for the COO "as we do not produce commodity products, but tooling machines that are quite complex. We did not have the choice to produce in a low-wage region like Asia or Eastern Europe. Today, we do not only sell a hardware machine that is absolutely excellent, but all the additional expertise and services. It is comparable to a super car with a bad driver. You can only push our technology to the limit if you know the process. This competence, today, is located in Switzerland". Furthermore, this factory serves as a marketing instrument and wants to attract qualified employees. The plant is seen as a marketing tool to promote MTC's products and innovation competences. Last, even though this was just a secondary reason for building the new factory in Switzerland, the business unit receives various subsidies, concessions and tax benefits from the Swiss government. The new plant will open in 2019.

4.5.2.4 High-wage location(s)

The strong Swiss footprint makes MTC more dependent on currency exchange rates than other companies. Big and instantaneous exchange rate changes can compromise MTC's cost structure or cause a need for supply chain changes. However, high-wage locations host all *lead* factories and function as know-how hubs for all other sites. Tasks and processes such as R&D, global IT or ramp-up are exclusively performed in high-wage countries. In addition, high-end products with a worldwide consumption of 80 to 100 machines per year are exclusively manufactured in Switzerland for several reasons. First, the supply chains in China are often more expensive compared to Switzerland. Second, splitting order volumes would lead to a loss of economies of scale. This also includes a shrinking negotiation power. Third, some special key components, which require highly accurate (grinding) processes cannot be manufactured in factories outside of Europe due to missing skills and insufficient support from technology providers. Fourth, MTC's Chinese suppliers are not able to achieve the required quality levels for several components. The chief procurement officer adds "if you want to produce a spindle in China, you need to buy all the components in Germany anyway. That is why it does not make sense to offshore manufacturing activities from Switzerland to China. Further, even though labor costs are lower in China, they only account for less than six percent of the overall machine price and are not that remarkable anymore". Finally, the informants mention that the reputation of high-end products manufactured in China is not very high. Therefore, only high-wage locations in Switzerland and Sweden are empowered to produce high-end products. In contrast, less technically advanced and high volume products are produced in Asia for the local market and partly for global customers.

In direct comparison, the two Swiss *lead* factories generate approximately 1.5 times as much revenue as all other sites together. The margin is similar for all locations. MTC's COO summarizes the discussion concerning high-wage locations as the follows: "We are convinced that if we offshore to a foreign country, it would be the beginning of the end. If we want to strive for a long-term engagement in Switzerland, stay competitive globally and grow as a strong company, we need to base it on know-how and knowledge. We think that is only achievable in Europe".

Table 13: Key implications (case A) (own illustration)

Implications	*Machine tool company*
I. 1	*Asian plants can be seen as an identical "copy-paste" of activities and developments done in Switzerland.*
I. 2	*Successful data management is needed for transparency, coordination mechanisms and quality improvements.*
I. 3	*Most location decisions are temporary considerations and affected by uncertainty. Hence, strategic site reasons can change over time (especially in Asia).*
I. 4	*Tasks and processes such as R&D, global IT, ramp-up, knowledge transfer, or manufacturing of high-end products are exclusively performed in high-wage countries.*
I. 5	*Building a new factory dedicated to digitalization unlocks production, R&D and marketing potentials as well as should attract qualified employees in high-wage locations.*

4.5.3 Case B: Building equipment company

The parent company is an industrial conglomerate with different business units and divisions. The largely independent business unit, hereinafter called building equipment company (BEC), manufactures building comfort systems, fire safety, security control, and energy management solutions. Headquartered in Switzerland, the business unit operates nine manufacturing sites in Asia, Europe and North America as well as 16 R&D sites. The mainly European footprint corresponds to the activities of the parent company. With more than 25,000 employees, BEC serves mainly B2B customers in local markets. A small share of B2C solutions complements the customer portfolio. Each year, more than 40,000 systems of BEC are installed, which makes the business unit one of the global leaders in building equipment. Further, BEC is renowned as a high-quality player in the market. Between 2014 and 2017, BEC's revenue developed by +17 percent. The main revenue comes from Europe and Middle East regions, followed by North America and Asia.

The business unit works on internal and external digitalization solutions. According to the informants, "digitalization can be a powerful weapon that should be used wisely".

4.5.3.1 Strategy and digitalization approach

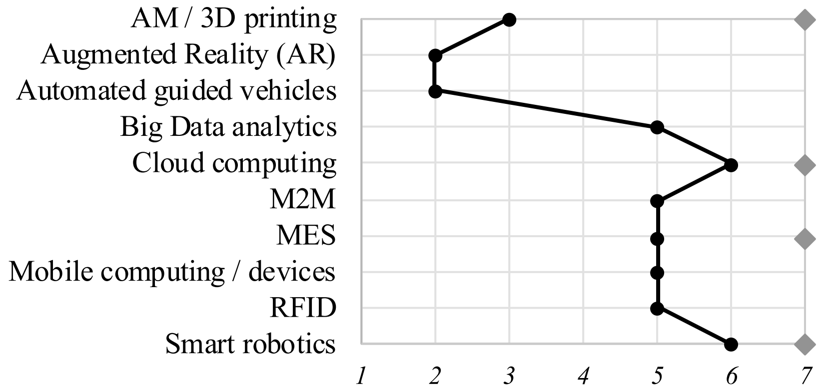
Digitalization is a major driver for BEC. Internally, the business unit promotes the use of digital technologies to increase efficiency and to keep production in high-wage countries. So synchronized production and material flow, shorter innovation cycles, execution of one-piece flow, and preventive quality management are the focus areas for BEC. From the external perspective, BEC sells digitally supported products that collect, analyze, store, and visualize data to create additional customer value. As full-solution providers are becoming more dominating in the market, BEC offers new services enabled by the availability of data. For instance, customers can benefit from reduced costs, optimized energy supply or increased building value created by BEC's solutions.

BEC followed an isolated approach with individual plant activities in the context of digitalization across locations until 2016. Since then, experts from the three leading locations (China, Germany and Switzerland) have developed guidelines and possible business cases for various fields, either separately or together. Thus, digitalization activities are structured in two ways at BEC. First, *lead* factories are in charge of identifying and developing digital solutions and, second, the activities are organized in project teams within the business unit and across the conglomerate, which operate as cross-sectional teams in line with the company's "operating model". The operating model is geared towards innovation, learning and efficiency at the conglomerate. Examples of such a cooperation are lean production, robotics, employee development, or logistics end-to-end optimization. In this respect, the head of production engineering operations mentions that "you do not walk alone, and we are very happy that we can share things with the operating model colleagues. Everyone can then develop solutions and later we bring it together. This is for our mutual benefit". In addition, both the *lead* factory activities and the project teams follow a strategic, long-term approach as well as an explorative or trial-and-error principle. Several pilots have demonstrated that both approaches can lead to lasting solutions at shop floor level. Currently, BEC is running more than eight projects regarding business cases and the implementation of digital technologies. These approaches are reinforced by top-down and bottom-up management.

Besides, BEC works together with technology providers and suppliers to unlock further digitalization potentials. From today's perspective, the access to and quality of local suppliers is better in high-wage areas. Consequently, the business unit outsourced many research or development activities in high-wage countries.

4.5.3.2 Technology portfolio and implementation

The business unit began with the automation and integration of processes in 2010. The sites are relatively independent in their choice of technology as long as the product quality is not negatively affected. Thus, automation levels and degree of connectivity vary worldwide. Accordingly, the level of automation ranges between 61 and 80 percent, while the level of connectivity is about 21 to 40 percent. Especially interfaces to suppliers are widely digitalized. Figure 15 provides an overview of the current implementation status of selected technologies.



(1: implementation failed / 2: observing / 3: researching and developing / 4: working on the implementation (prototyping) / 5: already in first use / 6: fully implemented / 7: impact on manufacturing network and/or plant role(s))

Figure 15: Technology portfolio and maturity (case B) (own illustration)

While a few technologies have a relative low maturity, cloud computing and robotics are at a high level ("fully implemented"). BEC was able to reduce direct production cost and number of employees in manufacturing by implementing robotics in the Western European sites. At the same time, indirect production cost, delivery speed and reliability, volume and design flexibility increased. Particularly product and process quality are reported to have risen above average. Hence, the application of these technologies offers enormous potential for R&D, production, assembly, logistics, or quality management.

At BEC, the level of automation and the degree of connectivity is going to change soon. Within the next years BEC will concentrate on software and ICT technologies (i.e. PLM, MES, data analytics). The first big step in the technology development roadmap is the development of MES. For this purpose, the Chinese *lead* factory will be the pilot for testing and implementation. This will minimize the installed SAP landscape by integrating customized MES solutions. On the other hand, BEC focuses on automation solutions. BEC has a few product lines with more than one million pieces per year. These product lines have been fully automated for quality and productivity reasons. For less automated processes, BEC developed and partly implemented smart robotics in form of lightweight and collaborative robotics. The aim is that collaborative robotics support manufacturing of small product quantities especially in high-wage sites.

4.5.3.3 Manufacturing network and site roles

The manufacturing network of BEC was consolidated a few years ago. From initially more than 15 manufacturing sites, the footprint was scaled-down to nine sites. Evaluation criteria were the number of employees, the level of competences and market relevance. The remaining sites are organized as profit centers. BEC sets up its manufacturing locations according to the product categories (comfort systems, fire safety, security control, or energy management). Products with a high added-value are not produced in high-wage locations right from the start. With one location in North America, four sites in Western Europe, one in Eastern Europe, and three plants in Asia (in China and India), the business unit serves most markets local-for-local. However, some products are shipped globally as only selected plants have the expertise to manufacture the specific product category. Capacities, products, competences, order sizes, and distribution channels are rather different at each site.

In general, the manufacturing sites follow a market or product orientation. BEC comprises three kinds of site roles. Although these roles are not rooted scientifically, they can be clustered according to the findings in chapter 3.4:

- *Lead*: Even though each site can do smaller improvement projects independently, pilot projects are traditionally conducted by *lead* factories to avoid redundancies. Two *lead* factories are located in Western Europe and one is in China. Internally, they are seen as the main production and R&D facilities as BEC has decided, from an overall perspective, that production needs to be close to R&D. Each plant is related to one major product type (product focus). All related tasks, such as product and process development, logistics support, troubleshooting, standardization, or continuous improvement are performed solely by the *lead* sites. For instance, the *lead* site in China is responsible for electronics while the Swiss *lead* factory is in control of fire safety products. However, the Chinese *lead* factory has a dual role. On the one hand, it follows a product focus, and, on the other hand, it is responsible for local supply (market focus).
  The *lead* factories at BEC have a support and coaching function, but no control function. To support other sites, the *lead* factories receive additional financial payments from the concern's headquarter each year. In the context of digitalization, BEC's *lead* factories are encouraged to identify, test and implement new technologies first. According to the head of global manufacturing, the major idea of a *lead* factory is the distribution of knowledge, which becomes even more relevant with new technology trends ("what we have thought in a few locations is made accessible to other locations in an optimal package").
- Associated plants: Each *lead* factory has several associated plants, which produce the same products as the corresponding *lead* factory. They have only limited competences and receive all support and guidance from the *lead* factories. Depending on their main strategic reason, they can be distinguished into *server* (proximity to markets) or *offshore* sites (low-cost production).

- Contract manufacturer: BEC operates a shared factory in cooperation with another business unit in Eastern Europe. It serves the European market by manufacturing high value-added products, which are too expensive for production in Western Europe. This contract manufacturer shows the characteristics of an *offshore* site.

Although not all employees are satisfied with the plant role setup, the upper management emphasizes that "it is important that everyone understands the strategy and the entire network […]. Employees need to appreciate that it needs overall profitability. We are a network of stronger and weaker locations and of high-cost and low-cost manufacturing. Only this makes us successful". Consequently, BEC introduced a peer coaching approach. In this way, up to three employees visit other plants one or two times per year. As a result, the employees receive a better understanding of the strengths and weaknesses of other sites ("[…] share knowledge, because we are all in the same boat").

Apart from the exchange between *lead* factory and associated plants, the exchange within the IMN is limited. As lower-cost sites in Asia mainly produce SMART (simple, maintenance-friendly, affordable, reliable, timely-to-market) products, technologies and processes have only little overlap with the structures in high-wage locations. The SMART products use standard technologies with reduced functionality. Further, they are economically priced for local markets and easily maintainable for service technicians in these regions. Hence, the Chinese *lead* factory exclusively supports Asian plants. Only a few standard technologies such as MES are transferred across locations.

The following figure 16 presents the plant-technology-competence framework of BEC. As the business unit works on various digital technologies, only the most important ones have been inserted. Additionally, some plants are pooled (e.g. North American and Western European plants). This figure makes it easy to see the various levels of competences of plants as well as the major technologies.

BEC is currently concentrating on data analytics and ICT solutions, which the salient number of triangle symbols makes clear. Especially, cloud computing (14) and MES (11) are in focus. While MES is being developed at the Chinese *lead* site, cloud computing solutions are provided by another business unit. The latter is fully implemented into production processes and partly into the supply chain, whereas MES is only available for the *lead* locations. Further, Big Data analytics (19) is developed and used in manufacturing processes in Switzerland. Automation and manufacturing solutions in form of smart robotics (2) are used in all sites except in the *offshore* plants. Additionally, collaborative robots (3) are implemented in Switzerland and Germany. Finally, AM (18) is at a research and developing stage. As with smart robotics, the Western European *lead* factories cooperate to develop AM technologies in terms of the operating model. In fact, these technologies affect the plant roles of BEC. On the one hand, the *lead* sites receive more development competences, and, on the other hand, digital technologies exploit the successful execution of activities and processes in all sites. Although BEC puts less emphasis on digitalization in lower-cost countries, digital technologies are partly implemented to speed up processes, enhance quality and relieve poorly trained employees.

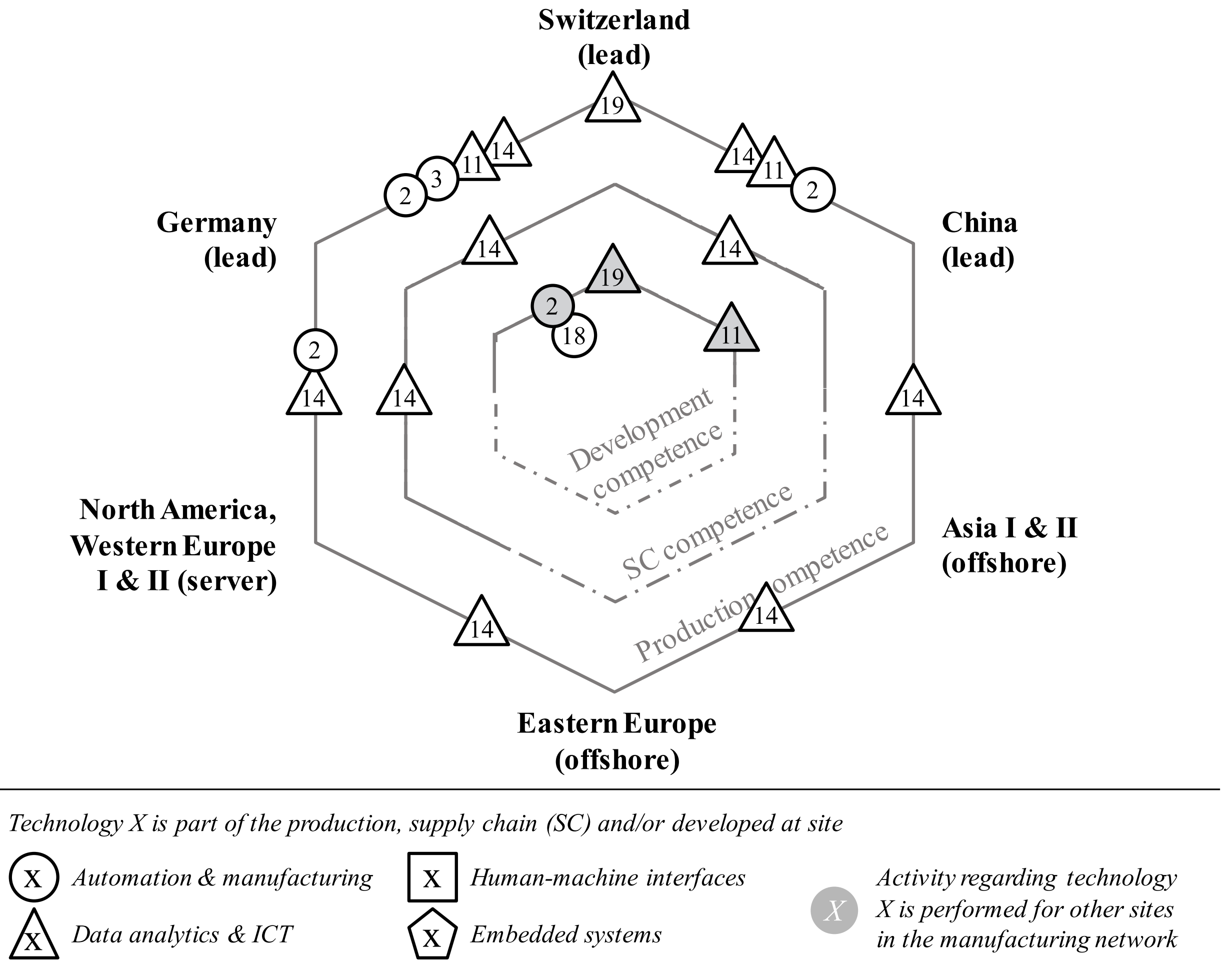


Figure 16: Plant-technology competence framework of case B (own illustration)

From an overall manufacturing network perspective, BEC focuses on cloud solutions, MES and smart robotics (see figures 15 and 16). These technologies are supposed to improve the management of manufacturing sites and cooperation. For example, MES is employed for coordinating and steering single plants in the network. Smart or collaborative robotics are used to support workers in high-wage countries as some processes are difficult to fully automate. So, these technologies enable partial automation and work simplification. Further, AM is believed to have a revolutionizing impact on global activities in the future.

Even though BEC's digitalization activities were rather isolated and decentralized until 2016, the plant-technology-competence framework discloses that today's activities are quite structured within the IMN. All development responsibilities are assigned to *lead* factories. These days *lead* plants get more accountability for new technologies (e.g. China for MES) and the strategic site reasons are better addressed thanks to the utilization of digital technologies. Only collaborative robotics are developed by other business units and suppliers and therefore not mapped in the framework. The framework also reflects BEC's intention to focus on ICT solutions. Even if there seems to be an imbalance between ICT and other technologies, this is desired according to the informants. In contrast to MTC, no redundancies can be found in the current setup. It seems that the consolidation of the IMN a few years ago resulted in a systematic and well-organized network design with clear responsibilities and tasks.

4.5.3.4 High-wage location(s)

The size of BEC's high-wage locations is relatively constant. Neither capacity extensions nor reductions are planned in the near future. These sites are responsible for R&D and manufacturing of the most complex products at BEC. The reasons for this distribution of tasks are based on the high qualification of the employees in high-wage areas. From today's perspective, "our lower-cost locations are not viable or at least we would take quite a lot of risks. If we closed the high-wage locations and offshored everything to China or Eastern Europe, I do not know how the company could work. Today, the technological process and knowledge is too sophisticated here [in Switzerland]. Maybe it will be different in 20 years". Thus, a combination of core know-how, risk assessment as well as support from headquarter reduces the pressure from other sites within the IMN on *lead* sites in high-wage locations. The combination of knowledge, product and process competences justifies and secures the high-wage locations. However, it does not mean that (established) products will not be offshored within the next years.

In summary, BEC does not consider reshoring activities as it has enough manufacturing capacities in Western Europe. Due to their distinct focus on products and markets, relocating products and volumes to Western Europe is not expected only because of digitalization activities. According to the head of global manufacturing at BEC, "digitalization is more of a protection of what we already have in Switzerland and Germany today". However, high-wage locations should be a leader for several topics such as lean management, innovation, product development, or digital technologies to stay as competitive as possible. That would allow them to stay competitive externally and within their own manufacturing network as not only pure labor costs are in focus.

Table 14: Key implications (case B) (own illustration)

Implications	*Building equipment company*
I. 6	*Collaborative robotics support workers in high-wage countries. As some processes are difficult to automate, this technology enables partial automation and work simplification.*
I. 7	*Hardware automation levels are higher in high-wage regions to reduce labor cost impact. The automation of decision-making through data analysis is a desired goal independently from plant location or process.*
I. 8	*The Swiss and German locations need to position themselves as technological leaders in different fields such as digital technologies, lean, innovation, or product development.*
I. 9	*The proximity to qualified suppliers and technology providers is crucial when developing and implementing digital technologies. This access is better in high-wage countries.*
I. 10	*A lead factory approach has a long tradition and the responsibilities are manifold. Selected plant roles from literature are more or less existing in the specific IMN.*

Before continuing with the other within-case analyses, the applicability and feedback regarding the plant-technology competence framework should be briefly discussed. As announced in chapter 3.4.6, the framework is only tested with the two case companies A and B. The reasons for this decision can be summarized as follows:

- Some companies operate large IMNs with more than 50 sites (e.g. case C). When mapping such large networks, the framework loses its clarity and simplicity. A table to structure the site portfolio would be more advisable.
- The interview partners of some case companies were not aware of the development activities of single plants. Hence, a structured mapping and discussion of each individual plant activity was not possible (e.g. case C, D and F).
- Some of the following case companies do not have definite plant roles. Even though the framework is expected to work without previously defined plant roles, the activities in the corresponding case companies are less structured (cases E and F).

Nevertheless, the framework has shown its strengths for quickly mapping technology activities in IMNs. It should be pointed out once again that the framework has a primarily supporting character; the author does not aim to test or improve it extensively. The representatives of the case companies A and B appraised the framework for being valuable and easy to use. An early consideration of the model can help to avoid problems and redundancies. As a recommendation, one interview partner suggested to split the "development competence" hexagon into product and process development hexagons.

4.5.4 Case C: Automotive supply company

The automotive supply company (ASC) is the largest business unit of an industrial conglomerate. ASC's product portfolio comprises components for electro, diesel and gasoline systems. In more detail, powertrain, safety, battery, assistance, and steering systems are developed and manufactured by the business unit. The largest customer market is Europe, followed by Asia and North America. The overall company's revenue developed by +59 percent between 2014 and 2017. With its corporate as well as business unit headquarter in Germany, ASC operates 52 manufacturing plants in more than 25 countries in Asia, Europe and the Americas. In total, the business unit employs more than 85,000 employees.

ASC pursues a dual strategy as being both leading provider and user of digital technologies. Not only are digital technologies useful tools for increasing quality and productivity. They are also seen as enablers for entirely new business models. According to the director of connected manufacturing, the efficient use of digital technologies "creates transparency and offers enormous opportunities for our sites and global network".

4.5.4.1 Strategy and digitalization approach

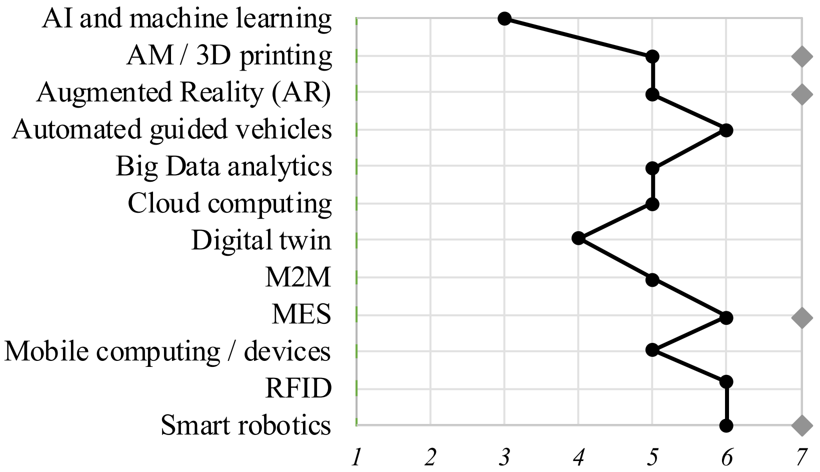
In 2009, the parent organization of ASC started recognizing the potentials of IoT. A corresponding working group at ASC was set up and later a cross-company "innovation transfer unit" was established. This transfer unit is the result of the consolidation of all digitalization activities of the parent organization and functions as a software and consulting provider for ASC. Nevertheless, there are still many digitalization activities, which are not performed by the transfer unit. Thus, ASC develops many digitalization solutions and digital technologies by itself. Especially, ASC's *lead* factories drive developments and distribute the outcomes within the entire IMN accordingly.

Internally, ASC treats digitalization as a toolbox for supporting the production system, which is the foundation and precondition for all technology implementations at shop floor level. In total, the business unit has around 200 pilot projects running at different sites. More than 50 projects have been completed. The aim of those projects is to identify and develop solution sets to enhance internal process performance. ASC applies a combination of top-down and bottom-up management and follows a strategic approach. After completing many pilots and projects, a plant manager emphasizes that "our explorative phase has been successfully finished. Now, we are strategically implementing and investing in selected business cases and digital technologies on a broader scale, which requires a strategic plan aligned to our production system". ASC implements digital technologies for two major reasons. First, transparency should be increased by efficient data analytics and, second, a decentralization of intelligence is intended. In a progressively dynamic environment with increasingly complex manufacturing methods and time pressure, decentralized decision-making should ensure manageable processes.

ASC makes use of the expertise and input from stakeholders all around the world. Regarding its digitalization activities, ASC collaborates with associations, customers, research institutes, and suppliers. While the latter provide full solutions or are involved in joint research, the other stakeholders primarily supply information and market research.

4.5.4.2 Technology portfolio and implementation

In the context of digitalization, the business units' employees have a vital role and digital technologies are supposed to support their successful work execution ("digital technologies serve the employees not vice versa"). Hence, most systems are not meant to replace workers but to assist them. Examples are, among others, barcode scanners, AR, collaborative robotics and all kinds of human-machine interfaces. The subsequent figure 17 gives an outline of the current most relevant technologies as stated by the informants.



(1: implementation failed / 2: observing / 3: researching and developing / 4: working on the implementation (prototyping) / 5: already in first use / 6: fully implemented / 7: impact on manufacturing network and/or plant role(s))

Figure 17: Technology portfolio and maturity (case C) (own illustration)

Different technologies are used to support planning, production, assembly, quality assurance, transportation, or logistics. With a degree of automation between 81 and 100 percent, ASC strives for maximum automation levels. By implementing smart robots and autonomous transportation solutions, production, assembly and logistics processes are largely steered autonomously in selected plants. RFID is used to monitor the status and condition of products or container boxes as well as to connect tools, machines, work pieces and inventories, which makes automated transportation possible. ASC was able to decrease direct production costs and the number of blue-collar workers as well as to increase product and process quality. However, the complexity of the processes also increased significantly. Thus, collaborative robotics are installed in German plants to better manage the rising complexity. They have a sensorial surface and autonomous object recognition, which allows safe co-working. They are not permanently mounted and can move freely within the factory. If production conditions or requirements change, the robots can be adjusted without (re-)programming by a dialog-controlled user interface.

ASC's expertise is strong in the field of production control and MES. An example is the control of intra-logistics, but also the application of external logistics with track & trace or sensor technology. The business unit employs a highly enforced MES to capture and process data in a standardized way. The MES allows a fully automated reporting and analysis of data for daily activities and plant benchmarking. Additionally, digital twins for products and tools are implemented in a few factories. They have a certain kind of decentralized intelligence and are connected to the MES. For example, selected shop floor tools facilitate process reliable tightening connections with the help of sensors and software functionalities. Thus, these tools avoid defects, accidental misuse and improve product quality. Besides, the digital copy comprises all handling and processing parameters.

Furthermore, AM technology is used in the R&D department as well as for the spare parts and small batch production. More than 50 fields of application have been identified. The manufacturing coordinator feels certain that "AM will be a standard solution for various products in the future […] and changes the way we are working in some factories".

Mobile devices at shop floor level are used at ASC to simplify maintenance work by providing all required data in real-time via smartphone or tablet devices. For instance, the time for some maintenance jobs was decreased by almost 75 percent for inexperienced employees. Moreover, AR technology is implemented in different business cases to transfer know-how and competences within the production network. Especially, experts at the *lead* factories are the driving forces that steer operations across sites. Further, AR supports (global) training and education activities. Another example for a working AR application is warehousing. Workers receive orders, tasks or instructions directly on smart glasses. The results show a significantly faster work execution and simplification. Although, in principle, the technology works in different plants, AR cannot be rolled-out worldwide since technical issues such as data security or safety aspects have not been solved completely.

Summarizing, data analytics and utilization have the highest priority for ASC, in combination with latest business cases in the field of AI or machine learning. Preconditions are the extraction of data from machines, network technologies to share data in real-time and analytics algorithms. As most machines and systems are connected and exchange data, the level of connectivity of the machine park ranges between 61 and 80 percent. In the future, the business unit will be striving for a connectivity rate of 100 percent as well as an OEE of 90 to 95 percent. By applying various digital technologies, ASC has achieved a positive effect on productivity gains, direct cost reduction and increasing capacity utilization (e.g. OEE). In some cases, the business unit reports productivity increases of up to 30 percent. Moreover, there is a positive impact on product quality, delivery speed and reliability. Nonetheless, it is not possible to clearly determine which proportion of this development is attributable to digital technologies and which proportion is based on a better process understanding and enforcement of the production system.

4.5.4.3 Manufacturing network and site roles

The business unit operates 52 manufacturing sites in Asia, Europe and the Americas. The basic equipment and technological setup are similar across sites. However, there are still significant differences in the level of competences and technology application. About one third of the 52 plants are highly innovative, one third have a little innovation competence and one third is passive. Especially costs, qualified employees and customer proximity are the key site location factors. Total cost consideration, however, is even more important for ASC, as the business unit manufactures mass-produced goods and its customers demand cost-effective products.

All sites have a distinct role, which was systematically derived. Although ASC did not make use of Ferdows' (1997b) plant role classification, the main roles can be found in the IMN:

- *Lead*: In total, ASC operates five *lead* factories for the whole network. They are strategically located in Germany and responsible for certain product groups. A *lead* factory is responsible for the initial introduction of a product (i.e. ramp-up), product and process development, definition of the manufacturing processes, technology development and implementation, standardization, initial sales activities, and ensures the transferability of the solutions to other locations. The latter is achieved by developing a process at a *lead* site to a certain maturity level that can easily be transferred to other plants. Regarding digitalization, the *lead* factories are increasingly responsible for IT concepts and upcoming technology trends such as

AR. Hence, from a configurations perspective, the functions and responsibilities in the network have slightly changed. A systematic three-step approach for testing and implementing digital technologies is enforced. First, pilot applications are developed in an isolated context in a *lead* factory. Afterwards, solution sets are combined to value streams to prove the usability in real processes and in context of the overall production system. Finally, the solutions are adopted by similar plants and rolled-out worldwide in the IMN.

In fact, as the tasks of a *lead* factory arise from its product portfolio, the development and emergence of new products can result in the creation of new *lead* factories. However, only certain factories have the competences and capacities to become a *lead* factory within the next five years. Other sites do not have the skills and know-how to take on such responsibility.

- *Contributor* and *server*: ASC operates most sites with particular regard to proximity to markets and customer reasons. Whether they are located in Western Europe, North America, some Asian countries or Eastern Europe, these sites have a high autonomy and can put into practice product and process innovations or smaller R&D activities independently from the headquarter. These sites can make adaptations and modifications to address local customer demands. Moreover, some of the plants can avoid customs, tax or tariff barriers as they are located in relevant markets (e.g. South America). Apart from the *lead* factories, these sites belong to the group of highly innovative or at least slightly innovative factories. As some factories have developed certain expertise and know-how in different fields, the *contributor* sites (e.g. Chinese plants) could also become *lead* factories for a specific (new) product within the next years.

  In addition, some plants in ASC's manufacturing network are operated as shared factories in cooperation with other business units. These sites were mostly set up by another business unit and ASC joined the existing location or vice versa. This setup is especially suitable for entering a new market or customer bases. For example, having access to trained employees and knowledge of regulatory standards in China enhances ramp-up and time-to-market. Other advantages are joint investments and assets, a similar technology park or shared overheads.
- *Source* and *offshore*: Since the main purpose of these sites is access to low-cost advantages, the autonomy and process complexity is lower compared to *lead*, *contributor* or *server* sites. ASC's *source* and *offshore* sites are located in Eastern Europe, India and China. However, the primary strategic site reason of Chinese sites is shifting gradually as the access to markets becomes even more relevant.

Lead factories are mainly responsible for process-critical technologies. For instance, an automated guided vehicle or AI are not necessarily process-critical elements in the sense that they do not fundamentally change anything about product creation. Such technologies could be tested or implemented on a small scale regardless of the *lead* factories. As all factories are managed as profit centers, they can either invest directly or receive financial support from headquarters to work on digitalization activities. Commonly, local developments and solutions are the preferred choice for improving a plants' performance. However, to avoid local systems and redundancies, the internal innovation transfer unit reviews individual solutions across all sites to enforce standardization. If corporate norms or standards are affected, the local development will be interrupted to ensure company-wide standards for processes and digital technologies. In recent years, the autonomy of some plants has led to redundancies. According to the manufacturing coordinator, "one can say that much has happened, which is not so good in terms of standardization and for our production system. Nevertheless, we have learned a lot and gained experience. For example, by using the same type of robot twice, we believe that we can facilitate different experiences at different locations. But now we are striving more for standardization and harmonizing the technological setup of sites".

The greatest technology levers for the manufacturing network are seen in robotics and the efficient use of data. Smart as well as collaborative robotics are implemented at different sites. The level of automation is comparable across sites, but especially workers in high-wage locations are assisted by collaborative robotics. These technologies offer a certain degree of automation and take over physically demanding jobs. At the same time, collaborative robotics collect data to further improve processes and products. Collaborative robotics are applied in *contributor*, *lead* and *server* sites to support workers and reduce direct labor cost. In general, while automation solutions are integrated in high-wage countries to reduce labor cost share, automation technology in lower-cost countries is used to boost process and product quality. Therefore, automation solutions and robotics also have a significant impact on plant roles. Although the network configuration is not physically changed because of digital technologies, tasks and coordination factors within the IMN change. Next to robotics, AR, MES and, in the long-run, AM are altering the network configuration and coordination (see figure 17).

4.5.4.4 High-wage location(s)

ASC has a high capacity utilization in its high-wage plants. Although the main requirement for each plant is to manufacture profitably, most high-wage locations must manage additional expectations, tasks and responsibilities that have evolved within the last years.

For example, all *lead* factories are positioned in high-wage locations. Hence, especially in R&D, product and process development, the high-wage sites are ahead compared to other sites and have an advantage for the next years. However, in terms of manufacturing, the sites worldwide are similar and manufacture identical, high-quality products whether they come from China, India or Germany. According to the director of connect manufacturing, “from an entire business unit perspective, a permanent existence of individual plants in high-wage countries cannot be guaranteed. In the worst case, if the high-wage locations are no longer profitable or are not able to maintain a knowledge edge, they will be under attack and have an uncertain future”. For example, as some Asian factories are very innovative and have developed expertise and know-how in certain product and technology fields, they could consequently become *lead* factories based on the maturity they have achieved.

However, on the one hand, there is a chance for the high-wage locations to derive new business models and develop new products thanks to the experience gained in the past. Accordingly, it is an auspicious opportunity for high-wage locations to further innovate new products and focus on efficiency gains in manufacturing processes. Another chance for high-wage sites, which have large capacities regarding knowledge or know-how creation, is to further push product innovations or to offer their services to foreign companies as external providers. Therefore, the high-wage locations at ASC must strive for a leading position concerning innovation in the field of technologies, processes, products, or business models. Otherwise, the future will become even more challenging for the high-wage factories.

Finally, it is not expected that digital technologies will be responsible for relocation activities, because plant location decisions are dependent on customers markets at ASC. Thus, digitalization is not a central lever for relocating manufacturing operations, but digital technologies can support existing manufacturing activities. In contrast, customer and market dynamics could enforce a relocation to Germany.

In summary, ASC sees its production system as the basis of any digitalization activity. Digital technologies are then useful tools or enablers to achieve certain process improvements. Many production lines and complete manufacturing plants have already been highly automated and digitalized. Such a high level of automation allows for an efficient and high-quality production with less direct labor effort. However, as the lower-cost sites become more and more advanced in different fields, high-wage plants must focus on innovation and efficiency gains. A plant manager from Germany concludes: “There is no alternative to implementing digital technologies. We have to be careful to keep pace and to not misjudge the world around us". This statement addresses both external competitors as well as competition within the own IMN.

A major challenge for ASC is the strong innovation and development potential of its plants. On the one hand, several factories are aspiring to become leading sites. Although the IMN was derived systematically, several highly innovative factories are ready to outrival existing *lead* factories in Germany. Hence, the internal competition is growing. On the other hand, plant autonomy has resulted in redundancies. The internal transfer unit is a consequence of these developments. It becomes obvious that the management of such a large IMN is not a single project but a lengthy task.

Table 15: Key implications (case C) (own illustration)

Implications	*Automotive supply company*
I. 11	*The production system is the foundation of any digitalization activity, while digital technologies are useful tools or enablers.*
I. 12	*AR is a promising solution to coordinate and steer manufacturing and service activities across plants. It offers the chance for lead factories to unite even more competences.*
I. 13	*Lead factories receive new responsibilities due to digitalization. However, roles and lead factories can change over time.*
I. 14	*From an overall perspective, plants in high-wage countries could be shutdown if the strategic site reasons change, they become unprofitable or do not create knowledge.*
I. 15	*High-wage locations have to become leaders in innovation (products and processes), R&D as well as for new business models.*

4.5.5 Case D: Control & automation company

The control & automation company (CAC) is a leading firm for process automation and technical training. The company offers products, services and systems in the field of pneumatic and electric control. In addition, it provides learning systems that are used by schools, institutes or companies to train specialists and technicians. Together with and for its customers, CAC develops tailored automation solutions. More than 20,000 employees develop and produce B2B products. The family-run business operates 10 manufacturing sites in Europe, Asia, North and South America. In 2015, the company opened a new factory in Germany, which is fully dedicated to digital technologies and energy-saving processes.

CAC is known as a premium provider in the market. Innovation is a top priority for CAC; more than 100 new products and patents developed each year are proof of that. As process automation technologies become more relevant and affordable for many businesses around the world, the market is continuously expanding. As a result, CAC's revenue increased by +27 percent between 2014 and 2017. Apart from CAC's intelligent products, which enable connectivity, communication and data analytics, the company has been working on internal digitalization solutions for years. CAC sees manifold potentials in doing so for increasing productivity and quality.

4.5.5.1 Strategy and digitalization approach

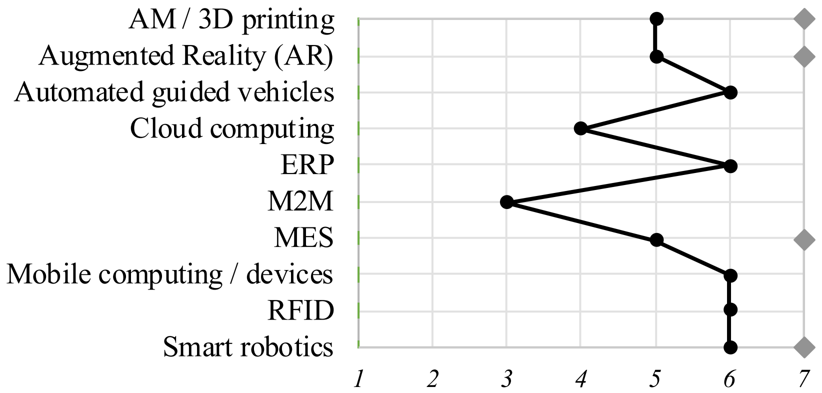
For more than five years, CAC has been extending its digitalization activities. Dedicated employees are working on projects and initiatives on the internal use of digital technologies. The company has a few lighthouse projects which drive integrated digitalization activities. CAC applies a combination of top-down and bottom-up management. This integrated approach makes use of decentralized competences in their units as well as of an overarching strategic framework. First, corporate management defines CAC's vision and strategy regarding digital technologies. This strategy is revised twice a year. In a second step, this vision is broken down into targets and individual strategies for each factory. The factory manager and his team then define what actions they will have to take and which digital technologies they will have to invest in to fulfil cost, delivery and quality targets. By detailing the factory strategies, tangible and operational goals can be defined for the employees at shop floor level. Currently, there are approximately 30 full-fledged projects regarding digital technology going on at CAC. Next to increasing production efficiency, the aim of the digitalization activities is to keep production in a high-wage country, to better enforce existing business models or to create new ones.

Although a few main sites are responsible for digitalization activities, each plant and business unit in CAC's network can perform its own research activities to promote and enhance digital technologies. As each plant has a defined investment budget, investment decisions regarding digital technologies can be made in a decentralized way and relatively independently from headquarter. However, regular central coordination is necessary to avoid redundancies. If a pilot turns out well, it is rolled-out to the whole company.

In close cooperation with research institutes, universities and consultancies, CAC pushes commissioned and joint research. Moreover, CAC is engaged in public funded research projects and is part of a governmental digitalization initiative. With reference to the company's COO, the proximity to these stakeholders is crucial for developing digital solutions. In the next years, CAC's high-wage locations are expected to benefit from the access to these partners and solution providers.

4.5.5.2 Technology portfolio and implementation

CAC employs different technologies in the field of digitalization. Whereas most catalogue items are produced in large quantities in highly automated manufacturing processes, customer specific developed products require intensive manual work. Nonetheless, AM, AR, cloud computing, MES, automated guided vehicles, mobile devices, and smart robots are being used in different operations in many plants. Figure 18 shows the current maturity stage of the most important technologies according to the upper management of CAC. By applying these technologies, CAC was able to reduce defectives, increase process and product innovations, generate additional sales by offering more individualized products as well as to increase transparency and improve decision-making.



(1: implementation failed / 2: observing / 3: researching and developing / 4: working on the implementation (prototyping) / 5: already in first use / 6: fully implemented / 7: impact on manufacturing network and/or plant role(s))

Figure 18: Technology portfolio and maturity (case D) (own illustration)

AM, for example, has made the leap from prototyping or pilot series production to small batch production. Another example is the implementation of mobile devices in diverse processes. Maintenance workers are supported by mobile devices (i.e. tablet computers), which leads to reduced repair time, improved maintenance services, productivity gains, more efficient workflows and employee satisfaction. Additionally, RFID as an identification technology is implemented in the entire manufacturing process as well as for supplier and customer handling. RFID records test results, logistics data, process and handling parameters.

Furthermore, CAC was one of the first companies in Germany that implemented collaborative robotics on shop floor for daily operations. As sensors and cameras monitor the movements of objects and environmental factors, there is no risk for an employee working hand in hand with the robot. In case of danger for humans, the collaborative robot slows down and eventually stops. Collaborative robotics are integrated to ease physically and ergonomically unfavorable operational steps in assembly. An outstanding example for the highest degree of automation are various production cells in assembly. These cells are modular and fully automated with standardized interfaces. Thus, the assembly line can easily be adjusted or extended according to specific needs. Such an arrangement of modular production cells can extend to 30 meters. Thus, some products are produced fully automated in these cells without any human interaction. Even raw material input, tool changing and final product packaging is done by smart robotics. The average level of automation is estimated at 55 percent across all plants. The degree of automation and digitalization mainly depends on the product type and employees. First, automation is only reasonable or economical for large product quantities. An exception are collaborative robots, which can be used for individual and small lot size production. Second, whereas conventional automation in form of machining centers and robotics is more typical for lower-wage locations, high-performance technology automation centers in high-wage countries require qualified employees for machine handling and operation.

In addition, CAC utilizes mature AR applications for the training of employees. By using smart glasses, employees are guided through their workplace, see moving directions or assembly steps. Further, AR is used for coordination activities within the IMN. Experts in a *lead* factory guide workers and service technicians around the world. This saves time and costs as the experts do not necessarily need to travel to other plants or customers for support or troubleshooting. According to the head of innovation and technology management, AR technology has a high impact on plant roles and IMNs by redefining the tasks and operating principles of factories. Nonetheless, the permanent use of AR glasses is not possible yet, due to ergonomic (weight), battery and habituation issues.

However, it is hard to tell whether all projects, technologies and activities are beneficial. The purpose of those trial-and-error activities is to learn about new technologies, gather experience and see where it is leading. There is a strong belief that these new technologies will lead to higher productivity and quality or lower costs. In close cooperation of R&D, production and IT, all projects and technologies are evaluated systematically. This evaluation of implemented solutions is done based on productivity gains, OEE or lead-time improvements achieved by digital technologies. By using a self-developed maturity tool, activities are categorized on a defined scale. Thus, CAC follows both a strategic long-term, but even more an explorative approach.

In the future, the company will focus on automation solutions including smart robotics, MES, AR and AM, which all have a direct impact on IMNs (figure 18). Further, collaborative robotics that can move autonomously in the factory building are on the implementation agenda for high-wage countries. Although the technological setup of CAC's plants differs, CAC strives for increasing automation and connectivity of machines worldwide to improve product and process quality. Since robotics are quality drivers, products have been reallocated and can now be produced at similar quality levels worldwide. Therefore, depending on the product and related technologies, digital technologies also support changes in product allocations.

4.5.5.3 Manufacturing network and site roles

The company is present in more than 150 countries and operates 10 manufacturing sites worldwide. Around half of the employees work in in the Western European sites in Germany and Switzerland. Other factories are located in Eastern Europe (Hungary, Czech Republic and Bulgaria), China, Brazil, India, and the USA. Furthermore, CAC has 20 small facilities that produce customer-specific solutions for local markets with only 5 to 20 employees per site. A highlight of its footprint is the latest plant in Germany. Between 2011 and 2015, CAC evaluated different location factors and planned a new *lead* factory in Germany, which is fully dedicated to digital technologies in production and smart products. The plant comprises automated and energy-efficient processes, latest digital technologies, high-quality products, and green-fabrication. For example, four fully automated production lines produce more than two million electric components per year without any employee needed. Hence, many aspects of digitalization are realized here. However, even such a highly automated and digitally supported plant does not mean zero employees – around 1,200 people are working in different departments at the new site. The new factory and its capacity are regularly expanding as CAC's business grows strongly.

CAC follows a market and technology approach in its manufacturing network. From today's perspective, Asia is the major growth market for CAC. This is why CAC builds its largest factory worldwide in China to be close to the customers. Thus, the Asian sites concentrate on Asian markets as they know the local business and technologies better. The same is true for European sites. With some exceptions, high-performance cutting machines that are used in Europe are not applied in Asia due to missing expertise in these regions. Instead, other concepts, which are less complex for the local market, are in place to fulfil similar tasks. As Europe remains an important market, the company will expand its capacities there as well. In this regard, the Eastern European plants function as extended workbenches for Western Europe. According to the COO, "twenty years ago, everyone went to China and now to Eastern Europe, because China is at least as expensive as Eastern Europe, but even further away from the European market. The most important thing is to constantly look at what needs to change, and which trends are important to us". Therefore, when introducing new products, it must be individually decided where to produce them. The first question is how complex are the products and, second, where are the customers? If the products are complex and the market is in Europe, Western Europe sites have a fair chance of being given responsibility for that product (type). However, if the products are sold in Asia, CAC produces them in China or India.

With regard to the 10 main factories of CAC, it becomes clear that the company has not established definite plant roles. Although it operates *lead* factories, these roles are not communicated explicitly, which makes it difficult to provide support for other sites. The following (implicit) plant types are identified based on internal discussions:

- *Lead*: CAC has defined several *lead* factories, which are advanced in certain technologies or products (figure 19). All *lead* factories are located in high-wage countries. These *lead* factories have more specialists, higher autonomy and more advanced equipment compared to other plants. As plant roles are not actively communicated, it is not possible to clearly separate between a technology and a product *lead* factory. For example, when it comes to plastic injection molding, a German factory oversees process improvement, standardization, troubleshooting, etc. If CAC has an issue with injection molding in its Chinese site, the company sends experts from Germany to China. In addition, the *lead* factory provides training and continuous improvement support. When it comes to valve technology, a certain factory is responsible for product design, properties, and testing, but may receive additional support from other *lead* factories in terms of different process technologies.
- *Contributor*: Proximity to market is the primary strategic site reason of the North American and Asian manufacturing sites. Although the Asian plants were initially set up as low-cost sites, they are mainly serving Asian markets. Especially China is no low-cost region for CAC anymore. Depending on the labor cost share of each product, production in China is at least as expensive as in Europe. Furthermore, these sites have a high degree of autonomy and competences based on the unique product portfolio produced in these plants. However, all *contributor* sites receive further product or technology support from the *lead* factories.
- *Offshore* and *source*: The Eastern European sites as well as the factory in Brazil tend to act as *source* or *offshore* locations. They have limited competences and especially the Eastern European factories serve as extended workbenches for Western European plants. Nonetheless, depending on the product portfolio, some

plants receive (temporarily) additional competences. Anyhow, their contribution to the overall IMN remains low.

- Central headquarter: The headquarter itself has no production capacity, but it plays a significant role for different technologies that are developed and implemented centrally. For example, ERP and testing machines are provided centrally from headquarter to avoid redundancies, conflicting interfaces or to ensure comparability. Thus, such technologies are specified centrally to circumvent long-term problems.

The product portfolio of each plant is quite different from those of the others, which offers only little space for cooperation and exchange regarding products. There are just a few products that run identically in two to three plants. Typically, each factory produces specific products from the large product portfolio with several hundred thousand variants. However, process technologies (e.g. robotics) and production supporting technologies (e.g. AR, MES) can be shared independently from the specific product portfolio. Figure 19 presents an exemplary overview. It becomes clear that support and responsibilities can partially overlap in case of different responsibilities for products and related process technologies. The subsequent figure is an extension of Tykal's (2009, p. 136) graphic, which concentrates on products in IMNs. Even though there are differences and implicit plant roles, the COO is convinced that "all plants operate at eye-level and are well adapted to the local conditions".

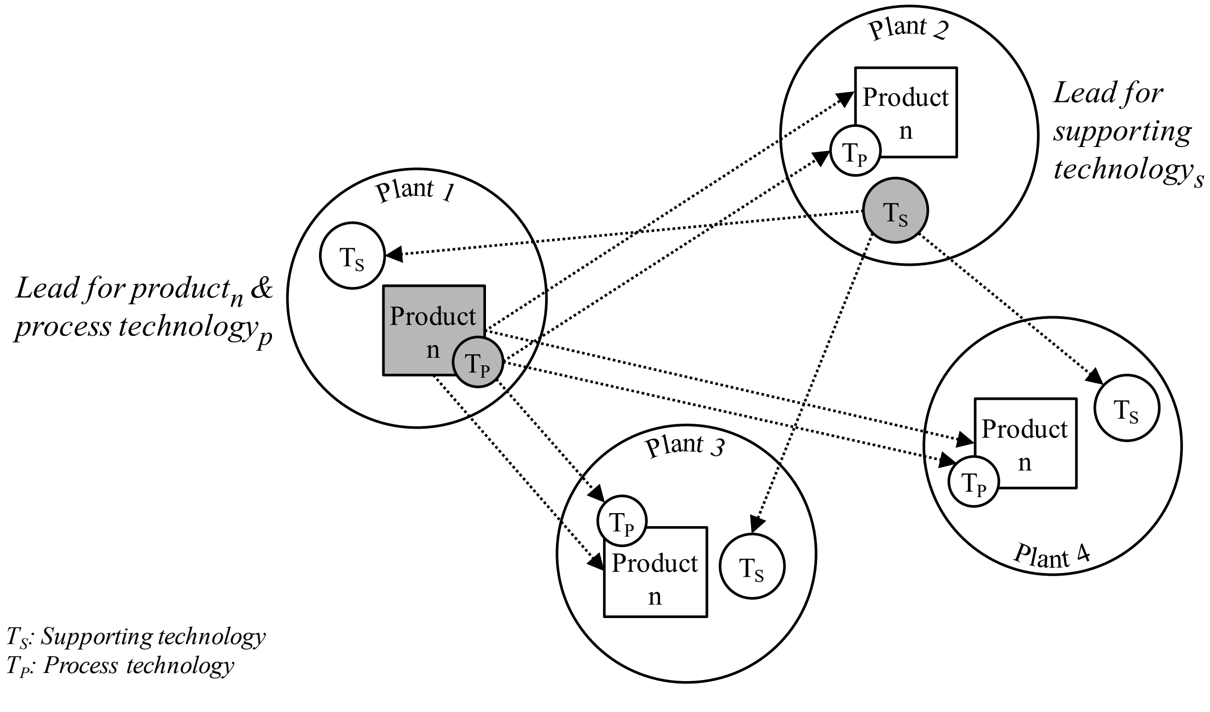


Figure 19: Lead factory concept with product and technology responsibility (own illustration)

The technological setup and use of digital technologies of CAC's plants differs from high-wage to low-wage locations. Typically, CAC strives for conventional automation in form of machining centers and robotics in low-wage regions. When more capacity is needed, more machining centers and robots are implemented. In Europe, high-performance machines are installed and operated by highly qualified employees. Thus, the level and kind of automation needs to be adjusted to the personnel qualification. Therefore, there are still significant differences in machinery worldwide and "automation is not equal to automation". Especially, high-performance machines, smart and collaborative robotics are currently reserved for high-wage locations. Further, AM technology is predominantly employed by *server*, *contributor* and *lead* sites to better address the strategic plant reasons. By manufacturing individual pilot series or small batches, the sites can serve individual customer needs. Moreover, the *lead* sites' competence levels are extended due to the application of AR solutions and mobile devices. The technology and domain experts are in the *lead* factories, but they still support workers and service technicians in other sites. Thus, the application of various digital technologies first impacts selected plant roles and then changes the network configuration by extending the responsibility areas of some plants in form of R&D, support or production competences. The establishment of a new high-wage facility in Germany directly changes the network configuration's footprint.

4.5.5.4 High-wage location(s)

Having a look at high-wage locations, CAC tries to exploit the know-how strengths of these factories. Hence, R&D for pneumatic and electric systems is typically done in high-wage countries. A special research area on bionic objects underlines CAC's innovative orientation and is exclusively performed by plants in Western Europe. Dealing with different replica of living creatures helps to learn about miniaturization, M2M communication, connectivity, energy-efficiency, self-organization, and root-cause relations. However, bionics is a more a research and marketing topic and has less relevance for manufacturing. Generally, there are two reasons for these activities in high-wage locations. First, it shows today's technological feasibility and, second, it helps to make the public aware of CAC.

In general, digitalization is seen as an enabler for keeping production in high-wage locations. On the one hand, it increases productivity levels and makes the sites in Western Europe globally competitive. The sites in Germany and Switzerland are rated as the most modern factories in CAC's IMN. High automation can unlock cost advantages in high-wage locations. The COO summarizes it as follows: "If your production is highly automated, then you can certainly be competitive in high-wage locations. When looking at the share of labor costs in the products, it is sometimes extremely low, only a few percent. We are seeing that here. If we manufacture products highly automated in high volumes, we cannot manufacture them cheaper in China. However, if you have products with a large share of human work, then of course there are advantages in Eastern Europe and China. That clearly depends on the products". On the other hand, digital technologies create new, qualified jobs that can be an opportunity for high-wage locations. From today's perspective, this development is a good argument for staying in high-wage locations due to the access to qualified employees, the local education system and knowledge.

Hence, the company is partly more exploratory and more innovative compared to other companies. CAC follows a long-term and learning-based approach to figure out which digital technologies are creating returns today and which will be promising in the future. The combination of automation solutions, human-machine interfaces and qualified employees are basic elements for CAC's future of production. Besides, CAC continuously adapts its plants and IMN according to market dynamics and trends. An example is the new, digitally supported site in Germany, which has also a marketing role. The aims are to increase internal productivity, create value for customers, ensure growth, and innovate leadership. The company is convinced that digital technologies are inevitable for being innovative and staying competitive. Nonetheless, from a global point of view, CAC experiences some setbacks and problems as the network is not systematically designed and several redundancies emerged in the context of digitalization.

Table 16: Key implications (case D) (own illustration)

Implications	*Control & automation company*
I. 16	*The ability to develop, apply and exploit new technologies enhances the competitive position of a manufacturing site.*
I. 17	*The combination of top-down and bottom-up management takes into account explicit shop floor knowledge and links it to strategic long-term visions and goals.*
I. 18	*Automation, human-machine interfaces and IT technologies have the highest impact on plant roles and IMNs.*
I. 19	*Complex products and processes are executed in high-wage locations, especially, if the customers are also located in this area.*
I. 20	*The company's new plant with its modern design and latest technologies is a lead factory, technological forerunner and marketing instrument.*

4.5.6 Case E: Electronic equipment company

Electronic equipment company (EEC) is one of the global market leaders in the chip industry. The B2B products are building blocks for most devices and systems and have become a vital part of everyone's daily life. The product portfolio ranges from chips for memory, security, communications and multimedia technologies to automotive as well as industrial electronics. The company's revenue developed by +63 percent between 2014 and 2017. More than 35,000 employees work in 36 R&D locations and 18 manufacturing plants worldwide. Its headquarter is located in Germany. All sites are based in Asia, Europe or the Americas. The company is continuously changing its global footprint. For instance, EEC recently opened a new building complex for production and R&D in Austria.

For many years, EEC has been permanently extending its digitalization activities. Internally, activities are driven by operations and externally by the possibility to offer new product segments. From a technological perspective, the digitalization project leader emphasizes: "We have finished our shop floor automation and are now successfully working on the analysis of Big Data".

4.5.6.1 Strategy and digitalization approach

EEC drives internal digitalization approaches to increase production efficiency and keep manufacturing activities in high-wage countries. Due to its commitment to high-quality and yearly expanding R&D efforts, EEC is seen as a technology innovator. Although there are some products that are exclusive to some customers, almost all products are global standard products.

Digitalization activities are decentralized at EEC. All sites within the IMN can develop digital technologies and improve processes by themselves. About 150 employees work on digitalization related projects. Besides, EEC has already successfully finished about 100 digitalization projects and has a project pipeline filled with ideas. These projects follow a strategic as well as explorative approach. Around 50 on-going projects show how much effort EEC puts into digitally supported manufacturing. Moreover, EEC pushes interdisciplinary project work in cross-functional teams to avoid isolated departments, silo thinking and missing cooperation within the company. Consequently, teams are (re-) assembled for specific projects to increase flexibility and dissolve hierarchical structures.

To share knowledge about digitalization within the entire ecosystem, EEC formed an internal community that functions as an expert group and meets every 4 to 6 months to discuss individual projects, transferability of solutions or key learnings. This might create awareness in the company, but also establish an internal specialist network. Outside of the organization, suppliers, technology providers and research institutes are meaningful partners for EEC. They provide information, conduct joined and commissioned research or offer full solutions. EEC is also engaged in on-going discussions with the focus on standardization in the context of digitalization and contributes to official committee work.

4.5.6.2 Technology portfolio and implementation

The electronic equipment sector has been highly automated for a long time compared to other industries and puts great emphasis on the use of digital technologies. In this sector, R&D and technology development is difficult and capital-intensive, whereas the price of the final product rapidly diminishes shortly after market launch. Hence, to make the large capital investments pay off, machine and technology utilization is at a high level.

The company's production process consists of two main production fragments called front-end and back-end. The front-end includes the raw chip production where electronic structures are applied to disks. This process can last 2 or 3 months. In the back-end small chips are cut off the silicon discs and mounted on a lead frame to connect them to the electric contacts. Finally, electronics are assembled in a polymer housing and tested. In total, up to 1,200 steps are necessary to produce a finished electronic product.

In direct comparison, front-end processes are significantly higher automated and digitally supported in contrast to back-end processes or plants. Automation technology such as robotics was implemented in the front-ends for two reasons back in the early 1980s. On the one hand, the processes are very standardized in terms of lot size, work pieces or transport boxes and therefore less challenging to automate. For example, the standardized wafers are guided through the factory by smart robots in a standardized box. The smart robots and autonomous transport systems place this box in front of a machine. After processing is finished, a robot picks up the box. On the other hand, the manufacturing processes require particle- and dust-free clean room production, which can be achieved by automated processes and less interference from workers or operators. Such automation allows for almost total quality control of nearly 100 percent, because all process steps are monitored. This explains the necessity to highly automate processes in the front-end. In contrast, back-end sites must handle different magazines, numbers of electric contacts and wires as well as individual batch sizes. These parameters make it difficult to automate back-end processes. However, at least in one of EEC's factories, the company started working with autonomous guided vehicles and robots to pick up or remove certain test boards as the back-end factory is located in a country with steadily rising labor costs. Finally, front-end and back-end have little points of contact. There are special solutions for front-end and back-end plants. However, some systems such as MES, RFID, monitoring system, or Big Data analytic solutions are globally implemented. In general, the company employs several mature digital technologies (figure 20), such as automated guided vehicles, Big Data analytics, cloud computing, MES, mobile devices, smart robotics, M2M, and RFID. These technologies are integrated in production, assembly, logistic, quality, maintenance, or service processes.

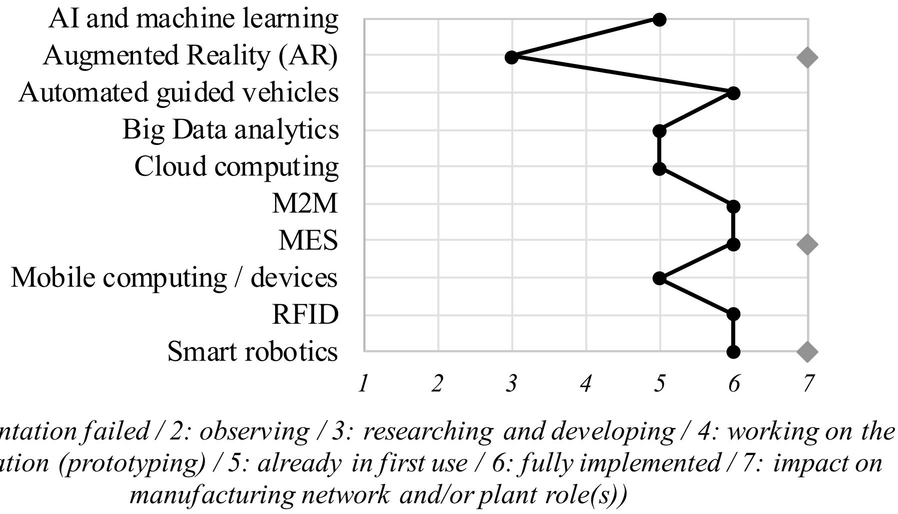


Figure 20: Technology portfolio and maturity (case E) (own illustration)

Full automation is not an alien concept for EEC. Front-end production lines are fully automated. Smart robots and automated guided vehicles act autonomously, move freely and fulfil several production tasks at the same time. Today, for example, one smart robot replaces 5 to 6 shop floor workers and is written off after 2 or 3 years. With more than 500 automated machines and smart robots in operation, some of EEC's factories reach an automation degree of almost 100 percent. Thus, direct production costs and the number of shop floor employees are decreasing. In turn, product quality as well as complexity of the processes are increasing. Similarly, as the machine park is highly connected, the connectivity rate ranges between 80 and 100 percent.

EEC reports efficiency and productivity gains by automation in production. Although a few solutions paid off quickly (e.g. clean room automation for quality improvement), some outcomes are not yet predictable. An example are AR solutions, which are at research and development stage. Their potential, however, is expected to be enormous. In addition to the training of employees, EEC has the future vision to remotely control other factories through effective data exploitation and AR technologies. A plant could be controlled remotely, or the respective employees could be instructed. Additionally, mobile devices are mentioned as an alternative.

A MES is operated in all 18 plants. It was first established in the late 1990s and has since been updated to meet current standards and requirements. Big Data solutions are also quite advanced. Especially, for quality management, production and logistics activities, data is analyzed and used for decision-making. The manufacturing excellence manager adds “what is new about *Industrie 4.0*, apart from the hype, is the availability of computing power, data and database techniques to evaluate data”. In this context, EEC works on AI solutions for further process and product improvements and automated decision-making. These solutions have partly been integrated in their front-end factories. Data is available for further analysis with focus on failure reduction, quality enhancement and process improvements. EEC uses a “pyramid structure” to develop their data management processes – from connectivity of systems to the prediction of future events and automated decision-making.

In summary, smart robotics is by far the most important technology for EEC’s processes, especially for the front-end factories. Additionally, autonomous transport systems also play a significant role. By applying digital technologies, EEC enhanced delivery dependability, reduced the number of defective goods, and increased transparency and product quality. As the automation levels of most factories have reached saturation, EEC focuses on data management. In the next years, data-based solutions such as MES, Big Data analytics, AI, or machine learning will be of great relevance to support EEC’s processes. AI and machine learning are seen as enablers to automate decision-making and increase efficiency. Therefore, a dedicated team for advanced data analytics in manufacturing was formed after data acquisition had become very advanced. The team is now responsible for ensuring the corresponding analysis and utilization of data and focuses on AI and machine learning to get even more out of data. Subsequently, full hardware and data automation is envisaged.

4.5.6.3 Manufacturing network and site roles

EEC operates 18 manufacturing locations worldwide. In general, the IMN can be delayered into front-end and back-end plants. These cost centers are located in Western Europe, North America, Asia, Eastern Europe, and Central America. Six of them are front-end factories and twelve are back-end sites. Five of the six front-end sites are located in high-wage countries in Western Europe or North America. EEC’s only large front-end factory in Asia is an outstanding exception compared to market-based practices. In contrast, only five back-end facilities are in Western Europe or North America. Thus, as the back-end processes are labor intensive, they are typically located in low-cost regions such as Asia, Eastern Europe or Central America (table 17). Even if the manufacturing processes of back-end plants do not require more skills or knowledge compared to front-end processes, the variety of products and batch sizes make it difficult to automate them.

Table 17: Manufacturing network overview (case E) (own illustration)

	Asia I	Asia II	Asia III	Asia IV	Asia V	Asia VI	Asia VII	Central America	Eastern Europe	North America I	North America II	North America III	North America IV	North America V	Western Europe I	Western Europe II	Western Europe III	Western Europe IV
Front-end	●											●	●		●	●	●	
Back-end		●	●	●	●	●	●	●	●	●	●			●			●	●

The company created a cluster structure for its IMN. Each plant is assigned to one of these clusters. For example, the four Western European, one North American and one Asian site form a cluster that works on digital technologies. These clusters are highly integrated, horizontally along the supply chain and vertically along the processes. The main internal stakeholders regarding digital technologies are industrial engineering, manufacturing IT and line management. While the line management in the individual plants tests, improves and implements technologies and processes locally, manufacturing IT and industrial engineering provide solutions across sites. Hence, each cluster hosts various functions. Other functions are organized at headquarter level such as corporate supply chain or IT.

Besides the front-end/back-end and cluster affiliation, EEC does not make use of plant roles. Each plant is operated autonomously. As a result, there are several different requirements and histories. These would take decades to integrate, because the applied technologies usually have life cycles of 10 to 15 years. For example, typical *lead* factory tasks such as process or product improvement can be conducted by each plant separately. Only corporate IT and the supply chain as well as R&D are centrally organized. The executive in charge of manufacturing excellence argues: “A *lead* factory idea is more propaganda. It is actually an alibi for factories in high-wage locations that are trying to establish such a lead quality brand to justify their high labor costs. Of course, I am exaggerating now. […] On the other hand, we have some natural *lead* factories that have been using and working on certain technologies for several years. Consequently, they have gained a leading function for a particular technology, which will eventually be rolled-out later”. Therefore, EEC has some “natural *lead* factories” for different technologies, which have a temporary character and support other plants as long as they have a technological advantage. Major responsibilities are best practice sharing, training and supporting others as a task force. Nonetheless, as the functions and responsibilities are often not officially communicated, the efforts are only partly successful. For instance, the *lead* factory for front-end plants is "probably" located in Germany. For the back-end factories, it is most likely in Asia (i.e. Singapore). Thus, leading plants are not restricted to high-wage countries. Consequently, there are also many redundancies in the IMN that "have to be eliminated after a certain time. As operations harmonize due to the requirements and developments of digitalization, there are also more and more standardization efforts".

In addition, the construction of a new plant in Austria, which was completed in 2015, is generally regarded as a milestone, as this new factory fully relies on digital technologies. Further investments of around 1.5 billion Euro for enlarging production capacities in this site until 2022 have been approved. Apart from R&D and production, it hosts a showroom for EEC's digitalization activities, which serves as a marketing and promotion tool. Interested parties and customers can visit and learn about a wide range of digital technologies, production processes and smart products. EEC chose Austria not because of customer proximity. The company's products are very light and easy to transport. As long as EEC faces no trade barriers or taxes, it can ship its products globally. Rather more important is the access to skills and knowledge, which such high-wage areas can provide. Qualified engineers or IT specialists are available and serve as the "backbone of the new site". The possibility of implementing the latest digital technologies in combination with public subsidies were additional location decision criteria for establishing the new location in Austria.

Form a manufacturing network perspective, the technologies AR, MES and robotics are vital (see figure 20). First, AR is being used for training and the expectation is a cross-site steering of the manufacturing network by using such solutions. Further, it should help to guide and support employees. Other mobile devices such as tablet computers are also valuable technologies in this context. Second, the rolled-out MES serves as a dashboard and coordination mechanism for the headquarter. By centralizing all manufacturing data, MES is used to coordinate activities within the IMN. Last, smart robotics support the automation of the front-end factories. These factories are mainly located in high-wage locations and therefore, robotics is vital for a balanced manufacturing network comprising high-wage and low-wage plants.

4.5.6.4 High-wage location(s)

EEC regularly invests in high-wage locations and expands capacities, because the market is growing significantly. As front-end and back-end processes are quite different, EEC focuses on front-end plants in high-wage locations. These factories are highly automated, connected and there is little pressure to save labor costs. This explains the large front-end factories in Western Europe or North America. The informants mentioned the fact that digital technologies have the potential to protect industrial operations in Western European countries. In combination with personnel and capital efficiency, a long-term positioning in the IMN can be achieved. As an example, the head of manufacturing excellence referred to the strong European footprint of EEC and high investments in the recently established plant. However, "there have been tendencies to offshore front-end operations to Asia, but better and more affordable digital technologies have stopped this trend. It is therefore no longer worthwhile to open a factory in Asia. Therefore, we continue to invest in high-wage locations". The benefits of low-cost regions cannot be exploited in a business where full automation is possible and affordable. Consequently, digital technologies have less impact on the allocation of products, but rather on the allocation of factories. Apart from the fully automated front-end factories, levels of automation and data connectivity are higher in back-end plants in high-wage countries.

However, back-end processes are labor-intensive and thus, back-end locations have been offshored to Asia for over 25 years. Europe has the advantage that robots harmonize far more quickly because the workforce is expensive. In Asia, robots are relatively expensive compared to the operators and the process is too complex. As a result, digitalization in Asia has a slightly different direction (except for Singapore). It is more about data transparency and quality improvement. Therefore, the company rather focuses on data automation or MES in order to achieve a high degree of transparency. As the back-end plants are considerably more difficult to automate, there is a risk of offshoring them to lower-cost areas. Concerning other offshoring activities, the digitalization project leader is sure that "neither R&D nor global functions will move to Asia, but into the cloud. Therefore, not Asians will do our typical Western European jobs, but computers".

Finally, having achieved a high level of automation, the company strives for data and decision-making automation. The strong footprint and high investments in Western Europe can be attributed to the proximity to skills and knowledge, subsidies and the application of digital technologies. Although digital technologies are not the main driver for establishing a new plant in a high-wage location, they are key enablers. EEC strives to transfer the learnings and benefits from the highly automated and digitalized front-end factories to the back-end factories. Even though the processes are quite different, the levels of connectivity and automation will be increased in the more expensive countries such as Singapore. For many other countries, EEC does not intend to expand automation in back-end processes as long as labor costs and product quality remain on a satisfying level.

Table 18: Key implications (case E) (own illustration)

Implications	*Electronic equipment company*
I. 21	*Both hardware and data (decision-making) automation are essential for efficiency gains.*
I. 22	*Digital technologies are key enabler for high-wage manufacturing and factory allocation. In more detail, automation technology and data-based solutions are relevant levers.*
I. 23	*Multiple sources, responsibilities and clusters lead to redundancies in an IMN.*
I. 24	*Leading sites evolved naturally based on technology competences. As the support functions and responsibilities are not communicated, the impact is rather limited.*
I. 25	*Access to skills and knowledge, technologies and subsidies are major location drivers.*

4.5.7 Case F: Home appliances company

The home appliances company (HAC) is a family-owned firm headquartered in Germany. HAC manufactures household solutions for kitchen, floor care and laundry applications for B2C customers. Laundry and kitchen systems are the largest product segments followed by cleaning systems. With showrooms and strategic retailer partnerships on all continents, the company serves consumers as well as professional customers (e.g. hotels). Compared to other players in the market, the products of HAC are high-priced, but also energy-friendly, reliable and durable. Being a high-end home appliances manufacturer in terms of quality and innovation, HAC's revenue developed by +22 percent between 2014 and 2017. In total, HAC operates 12 manufacturing sites, which are mainly positioned in Germany to be close to its target customer base in Europe. About two third of the more than 15,000 employees are working in Germany.

Digitalization is an important enabler for the company, both from an internal and an external perspective. For example, HAC's smart products are equipped with connectivity and learning systems. Within its manufacturing sites, the company uses a wide range of digital technologies for production improvements, but also to "unlock the full potential and make the sites even more competitive" (according to the division director).

4.5.7.1 Strategy and digitalization approach

The overall aim of HAC's digitalization activities is to increase production efficiency and keep production activities in high-wage countries. Related digitalization activities are currently decentralized at HAC. The independent plants in Western Europe can evaluate, test, implement, and invest in digital technologies without exchange with headquarter or other sites. Only the extended workbenches in Eastern Europe as well as China need approval from their *lead* sites in Western Europe. This decentralized approach led to various redundancies in process and technology developments. For future digitalization activities, the company intends to extend the areas of responsibility of the existing *lead* factories or set up new CoE for specific tasks. Moreover, the whole company will be less structured by product types, but in the form of technological clusters. While the individual product segments such as laundry or cooking solutions have so far been considered as separate entities, it is now intended to interdisciplinary link the areas to create a holistic eco-system within HAC. This change process is a major hurdle, since the individual employees have not yet learned how to think in cross-product platforms. Thus, a big challenge for HAC is the digital transformation on a horizontal level and the establishment of common platforms for processes and technologies. In the future, different clusters are expected to plan digitalization attempts with the help of an activity map. The desired advantages of such a cluster structure are to avoid silo thinking, elimination of redundancies, faster project results implementation, and reduced competition for resources within the IMN.

Although each site is allowed to develop and implement solutions individually, HAC follows a strategic approach concerning digitalization. Hence, each activity requires a pre-defined ROI and resilient roadmap. With more than 40 digitalization projects going on and 10 finished projects, HAC is an active player and continuously invests in digital technologies and solutions. This attempt underlines the company's innovation driven approach. Thus far, all results of the finished projects have been integrated and used permanently in different processes.

Furthermore, HAC faces the challenge of obtaining and evaluating customer data efficiently. Since the company sells its final products through intermediaries, it is a major problem to collect data from consumers. For that reason, HAC started strategic partnerships with retailers, other companies and even competitors to consolidate its position in the market and to offer one-stop solutions for customers. Other important stakeholders are suppliers.

4.5.7.2 Technology portfolio and implementation

HAC employs a wide range of digital and automation technologies. Figure 21 outlines their currently most relevant technologies. Whereas some of the technologies are purchased externally, HAC's engineers and process specialists develop most technologies and related processes internally. For that reason, the company operates a large engineering department that focuses on internal process optimization and automation solutions. An example is internal material handling. Thereby, production and assembly steps are either combined to avoid transportation between the processes or automated guided vehicles are implemented. Both autonomous forklifts and crane systems transport work pieces from one production step to the following. They also pick up raw materials from storage or work pieces from the buffer zone. This procedure is further improved by RFID. As a consequence, only a handful of workers are necessary to keep operations running in a large factory building.

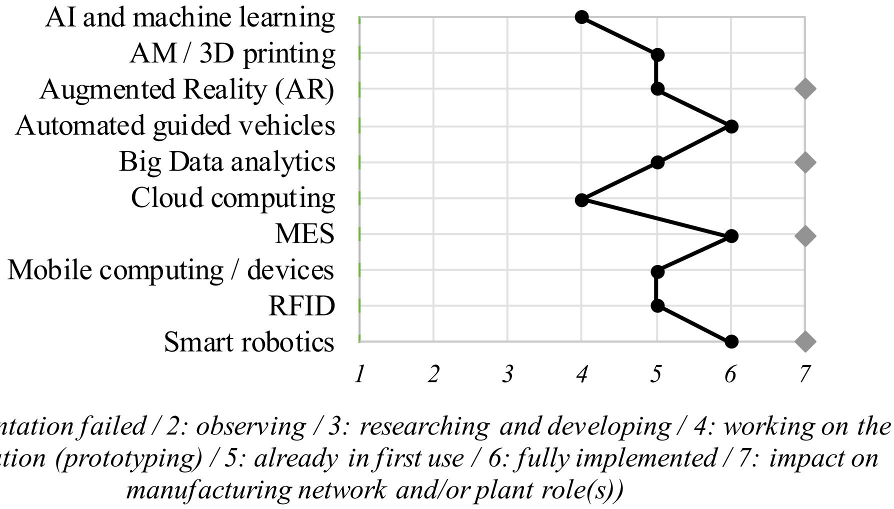


Figure 21: Technology portfolio and maturity (case F) (own illustration)

Smart robotics is integrated into almost all manufacturing processes. For example, the manufacturing of approximately 900,000 laundry systems in a single plant per year is only possible due to high automation levels and robot implementation. Bending, welding and painting are operations performed by smart robotics. The degree of automation ranges between 70 and 100 percent depending on the product group and factory. By using different types of robots, the company was able to increase product quality, process stability and robustness, but also to increase process complexity. Conversely, direct labor costs have been significantly reduced, while indirect labor costs for engineering and process improvement experts are rising. Besides, HAC has implemented first collaborative robotics to support workers in different operations in high-wage locations. For instance, these collaborative robots hand over or assemble components to relieve HAC's employees.

AM is partially used for spare part production, but mainly for prototyping in R&D. However, the production of final components is not possible yet due to the limited quality levels and surface finish of AM technology.

The collection and analysis of data are major focus areas for HAC. The company investigates solutions and applications in different fields such as Big Data analytics, AI or machine learning. For instance, machine learning is used for preventive and partly for predictive maintenance. Further, it enables machines and transport systems to improve their sequences of movements due to learned patterns and "experiences". Similarly, AI is expected to optimize manufacturing processes by reconfiguring material flow, buffer time, sequence, or cycle time. Additionally, a standardized MES and IT system is implemented at all manufacturing sites worldwide. It allows the collection and processing of data, which ultimately is used for the steering of processes and facilities. HAC's vision is an autonomous and intelligent planning of working hours and flexible worker organization according to demand peaks or bottlenecks. According to the division director, HAC profits most from data analytics and systems within the manufacturing network. The cooperation and exchange are facilitated by different IT systems and a standardized MES.

Digital twins for products and processes are partly implemented in selected plants and for specific products. A virtual copy of all parameters, process and handling steps enables a unique identification and traceability of each product. On the one hand, this enhances transparency in the manufacturing processes and, on the other hand, systemic production failures and quality issues can be recognized more easily in case of quality claims. The digital twin also manages information about product user behavior, services and guarantee measures.

AR solutions and mobile devices on the shop floor are implemented in selected plants. Mobile devices allow a provision and access of real-time data at shop floor level. The company is testing and using AR technology in different fields. In fields such as assembly or maintenance, workers are supported with required information and instructions on a head-mounted display. AR is also used in product presentations and showrooms to enhance customer experience and acceptance. Furthermore, the technology is tested for external service offerings at customer level. Another promising field would be the exchange and guidance of workers across manufacturing sites.

The application of different digital technologies facilitates increasing process transparency, quality levels, productivity (e.g. faster process execution) as well as delivery speed. Within the next years, the company will focus on further automation and data analytics. First, the company wants to increase the levels of automation to 100 percent in Western Europe. By minimizing transportation routes and investing in autonomous transport systems, material handling should be improved and manual material flow eliminated. Smart robotics could replace routine operations and boost quality in critical processes such as painting. Second, AI, Big Data analytics and machine learning are estimated to unlock groundbreaking potentials regarding process efficiency. Thus, many internal experts are now working on such solutions to enhance and reconfigure existing processes.

4.5.7.3 Manufacturing network and site roles

HAC operates 12 manufacturing sites worldwide. Nine of them are located in Western Europe, two in Eastern Europe and one in Asia. An additional site in Eastern Europe is under construction. Around 30 percent of the customers are located in Germany, 50 percent in the rest of Europe and approximately 20 percent in Asia, Africa, Australia, and the Americas. Each plant is responsible for a specific product type such as floor cleaning devices, kitchen products, or washing machines. Thus, the dependencies as well as points of contact are limited.

The company does not make use of plant role models. Typically, each site is fully responsible for one product segment. However, some indirect roles have evolved naturally:

- Independent player: Most of HAC's factories are independent players. The plants have full responsibility for all processes and activities related to one product segment. This includes R&D, manufacturing, sales, and marketing. This is why each plant employs many experts for different activities. This fosters different approaches and developments concerning digital technologies. The independent players in Western Europe are highly specialized and have the highest autonomy.
- *Lead*: The company operates three *lead* factories according to the main product segments kitchen, floor care and laundry. All three *lead* factories are located in the home country in Western Europe. They have the same responsibilities as the independent players, but on top each is responsible for one associated plant. Hence, besides R&D, manufacturing and sales activities, the *lead* factories care about the developments and processes in the associated plants that produce the same product segment. Problem-oriented tasks such as trouble shooting are done for other sites. Additional responsibilities include continuous improvement, technology roll-out, process and product improvement, standardization, training, or best practice sharing. Consequently, the *lead* factories are responsible for their own strategic development as well as for the development and growth of an associated plant.
- Associated plants: The sites in Eastern Europe and Asia are extended workbenches for the plants in Western Europe. Each of these plants is assigned to a *lead* factory. For example, the Asian site produces floor-cleaning systems and relieves the floor-cleaning *lead* factory. Being guided by the *lead* factories, associated plants have a low autonomy and competence level. Although plant roles are not officially applied

by HAC, the plants in Asia and Eastern Europe can be classified most likely as *offshore* sites.

Without exception, all associated plants have a high degree of utilization and manufacture standard products with high volumes and no variants. These products are typically inexpensive and constitute the technological low-end product portfolio of HAC. In contrast, complex, expensive and high-end products with many variants are exclusively manufactured in *lead* and independent factories in Western Europe. The major reason for this allocation is the problem of finding enough qualified employees in Eastern Europe and Asia. Recently, the company introduced a product entry-line to increase market share in the lower-tech markets. Depending on market developments and new customer segments, additional plants are conceivable in Asia or the USA as these markets are growing. At present however, exporting products from Europe is more cost-efficient than building new facilities in these areas.

The technological setup varies across locations, which is attributable to the different product portfolio of each plant. The product type does not only determine the complexity of the specific object, but also the volume. For instance, the yearly output of laundry systems exceeds 900,000 pieces, whereas less than 20,000 coffee machines are produced per year. The former requires full utilization in form of three- or four-shift operations and the latter one-shift operations. Thus, only products ordered in large quantities are produced with the assistance of automation solutions and robotics. Furthermore, sites in high-wage locations have a higher degree of automation compared to sites in Eastern Europe and Asia.

The sites in Eastern Europe offer a good infrastructure and significant logistical advantages compared to remote locations in Asia. According to the division director, the company would not invest in Asia again for two reasons. First, the market is not as attractive as expected several years ago and, second, the distance to the *lead* factories is too large to easily support, control and steer operations. In direct comparison, the overall costs – including logistics and labor costs – are similar in Eastern Europe and Asia. Therefore, investments in Asia do not offer additional benefits for HAC.

4.5.7.4 High-wage location(s)

The company strategically splits its product portfolio. While complex and high-end products are manufactured exclusively in high-wage countries, cheaper and less sophisticated products are mass-produced outside Western Europe. Although a high diversity of variants is more difficult to automate, these products are reserved for factories in high-wage areas. The limited know-how and the lack of qualified employees in Asia and Eastern Europe provide a location advantage for Western European countries. From today's perspective, "it would be not possible to offshore any R&D activities to Eastern Europe or Asia as they do not have the required know-how and competences", according to the division director. Finally, taking a leading position in process, product and technology innovations, the high-wage locations can strengthen their knowledge advantages. As HAC's high-wage sites have large R&D and development capacities, this is a chance for the factories to further develop worldwide solutions as development activities and examination of digital technologies are rather limited outside Western Europe. Naturally, after rolling-out new technologies to other locations, these facilities can also profit from the technological advancement, but the key to success is to continuously be the leader and one-step ahead compared to other sites and competitors.

On the other hand, low-cost factories are an important supplement for the high-wage sites as product prices are declining and pure efficiency gains in high-wage locations cannot absorb this development. Especially for inexpensive, low-end products, which are sold in a highly competitive market, the low-cost facilities are central manufacturing locations that fulfil a company-wide quality standard. However, the head of production system planning argues that "the brand "made in Germany" is still a unique selling point and an important quality label. Especially in a B2C market, this kind of brand procures additional sales and quality promises. Our customers rely on our products and prefer products from Germany. However, if they buy a low-end product they have no choice and receive a product from outside Germany. […] Being a quality and innovation leader in our industry in combination with the "made in Germany" brand and a long tradition as a family business makes us a credible provider for consumers and professional users". In addition, HAC continuously invests in its high-wage locations in Western Europe as approximately 80 percent of customers are located in Europe. For example, around two third of the yearly investments in R&D, capacity expansion as well as technologies are invested in Germany. In fact, the family-owned company has a long tradition in Germany, which makes giving up production in Germany and offshoring activities to foreign countries highly unlikely. However, an expansion of the current footprint is possible. If new markets emerge or customer segments change, new (additional) sites are conceivable in the USA or Asia.

In conclusion, proximity to customers, access to knowledge and qualified employees as well as a reasonable cost structure are main location factors for HAC. At present, the high-wage locations can profit from the former aspects more than other sites do. To improve the cost structure, HAC develops and implements a wide range of digital technologies. Significant gains in product quality, process stability, transparency and productivity due to technologies such as smart robotic, AI, automated guided vehicles and more, enable a cost-efficient production in high-wage areas. The division director emphasizes: "Our plants in Germany have an enormous potential for efficiency gains. Although we have been doing lean production for many years, we still have potentials to improve material flows and reduce waste. Equally relevant are hardware and data automation. With the help of autonomous transport systems and robotics, we minimize the human workforce, labor cost and simultaneously increase quality levels. The automation of data due to machine learning or AI will unlock similar potentials within the next years".

Table 19: Key implications (case F) (own illustration)

Implications	*Home appliances company*
I. 26	*While automation in high-wage countries reduces share of direct labor costs, it is implemented in lower-cost regions to increase process and product quality.*
I. 27	*Sites in Eastern Europe offer a good infrastructure, similar cost structures and significant logistical advantages compared to (remote) locations in Asia.*
I. 28	*Complex and high-end products with many variants are typically manufactured in high-wage locations. The quality label "made in Germany" is meaningful for B2C businesses.*
I. 29	*Relocation activities are less likely for family-owned companies with a long history in high-wage locations.*
I. 30	*The combination of product, process and technology leadership justifies and secures the activities of plants in high-wage locations.*

5 Cross-case analysis and discussion

Apart from the within-case comparison, a systematic cross-case analysis is "a key step in case research" (Voss et al., 2002, p. 214). Eisenhardt (1989, p. 541) proposes "the idea behind these cross-case searching tactics is to force investigators to go beyond initial impressions, especially through the use of structured and diverse lenses on the data". Hence, a cross-case analysis should deepen, refine and generalize the findings from the within-case analysis by showing similarities and differences of management practices. The subsequent chapter focuses on the essential findings from the cross-case analysis, although several additional promising coherencies and management practices were identified. Further, it addresses the remaining RQs.

Some excerpts have been published or presented in the following outlets:

- *Benninghaus, C., Budde, L., Friedli, T., & Hänggi, R. (2018), Implementation drivers for the digital industrial enterprise, in: International Journal of Production Economics, In review.*
- *Benninghaus, C., Elbe, C., Budde, L., & Friedli, T. (2018). Digital Technologies – Evolution of production in high-wage countries. Final report. Institute of Technology Management at the University of St.Gallen, St. Gallen.*
- *Benninghaus, C., Lützner, R., & Friedli, T. (2016). Industrie 4.0 – From a management perspective. Final report. Institute of Technology Management at the University of St.Gallen, St. Gallen.*
- *Benninghaus, C., Wenking, M., & Friedli, T. (2017). Impact of smart manufacturing solutions on the strategic management of international manufacturing networks. In 28th Annual Production & Operations Management Conference (POMS). Seattle, Washington, USA, May 5-8, 2017.*

5.1 Digital technology implementation

Almost all digital technologies that have been identified in literature (chapter 3.2) are applied by one or more of the case companies. Although the maturity of application varies, it shows the potential and importance of digital technologies for future production. Moreover, all case companies use digital technologies from different technology classes. This finding emphasizes the importance of interoperability between systems, which has been confirmed by Kang et al. (2016), Kühnle & Bitsch (2015) and Mittal et al. (2017). The fact that digital technologies have a wide diffusion and are developing at an exponential pace might explain the popularity of digitalization (Schreckling & Steiger, 2017, p. 6).

The following figure 22 outlines and summarizes the utilization of technologies of the case companies. It shows the kind of products (from commodity to unique products) and what kind of technologies the case companies employ (from digital to conventional technology).

For example, commodity products are characterized by standard components, basic product design, few product changes, and less product innovations. Unique products are complex, R&D intensive, have many variations or features, and require frequent changes (Ferdows et al., 2016, p. 73). On the vertical axis, conventional technologies are typically standardized, technology transfer is less challenging and know-how widely available. In contrast, the level of experience is limited, technology transfer difficult, innovation more frequent and development done in-house for digital technologies. The figure is an adaptation and modification of Ferdows' (2008) work[6].

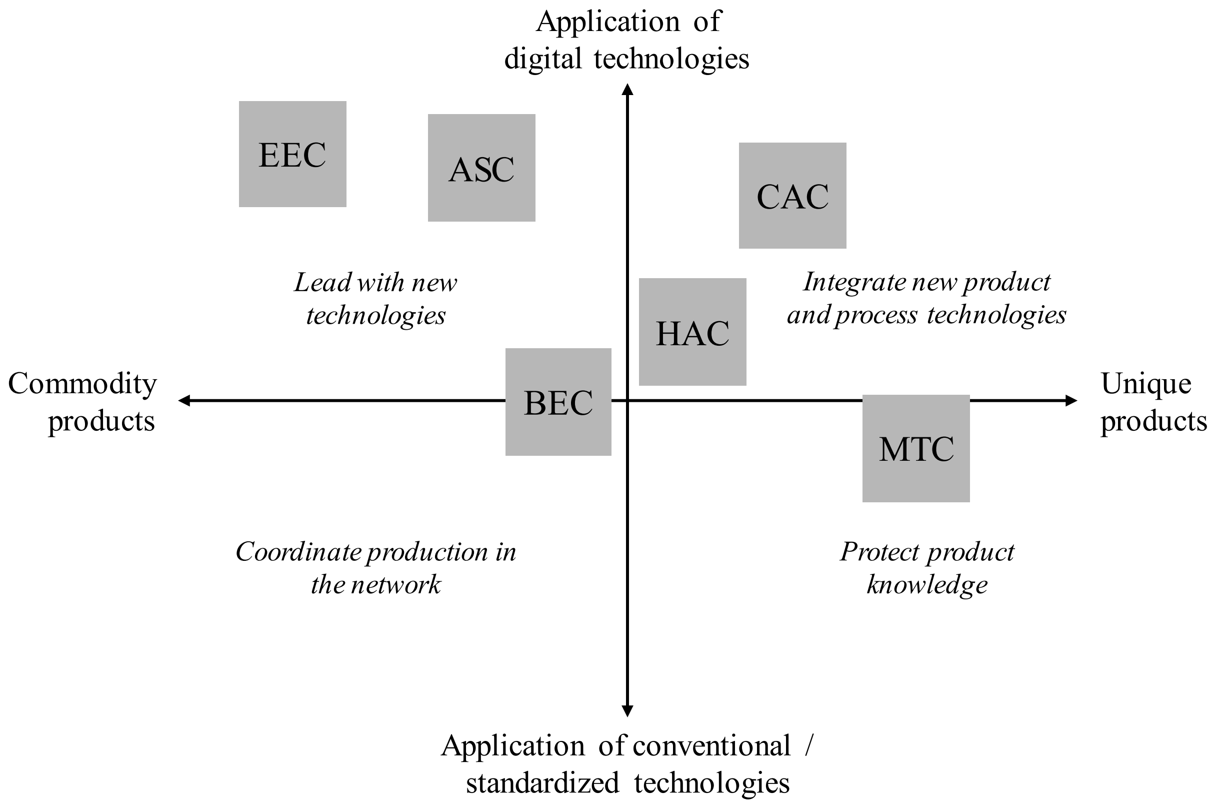


Figure 22: Framework for product/technology network classification (own illustration)

Whereas EEC is using a wide range of digital technologies and relies on high levels of automation and connectivity, automation levels of MTC are lower as the business unit's products are manufactured according to a make-to-order principle. In general, the levels of automation are the highest at EEC and ASC, followed by HAC, BEC, CAC, and MTC. Similarly, EEC possesses the highest degree of connectivity followed by MTC, BEC and ASC.

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[6] *The original framework by Ferdows (2008) distinguishes between "proprietary and standardized production processes" instead of "digital and conventional/standardized technology".*

MTC is the only company located in the bottom-right quadrant. Its manufacturing processes are complex, largely manual and only marginally supported by digital technologies. A strategic direction for MTC should be the protection of knowledge and products as the company cannot generate profit from their manufacturing processes or plants (Ferdows et al., 2016, p. 66). Consequently, MTC and HAC limit knowledge diffusion by concentrating strategic components and know-how in high-wage locations.

CAC and HAC primarily manufacture relatively complex products with the use of digital technologies. They should focus on the integration of new product and process technologies (Ferdows et al., 2016, p. 65). Ferdows names these IMNs “rooted networks” (Ferdows, 2008, p. 156). ASC, EEC and BEC are positioned in the upper-left quadrant. Their products are less individual compared to the other case companies, but their utilization of digital technologies is similar. The perspective for these companies is to lead with their (digital) technologies and drive process innovation as competition in their markets is high. For instance, EEC’s competitors operate big factories in lower-wage countries to exploit economy of scales and offer competitive market prices. In addition, ASC’s automotive supplier market is constantly under cost pressure. However, Ferdows et al. (2016, p. 66) add that the conditions for companies in the upper quadrants are typically more sophisticated if they operate factories in high-wage countries. Companies in the bottom-left quadrant produce simpler products with standardized or conventional technologies. Although no case company is (fully) positioned in this quadrant, selected plants of BEC, ASC and EEC belong to this class. The strategy for these company’s sites is to coordinate manufacturing in the IMN to unlock efficiency gains. A typical finding is the outsourcing of activities to contract manufactures as it is done by BEC.

Figure 22 is an abstract overview to structure the cases. The classification indicates the different levels of technology application and kind of products. There are various reasons for the different application spectrum of digital technologies: company-specific factors (e.g. size, resources, investments, strategy), industry-specific factors (e.g. electronics) and location-specific factors (e.g. social, legal, environmental, economical, political). A similar classification was developed by Buckley & Casson (1991, p. 33). A look at the individual IMNs of each company shows that most companies have plants meeting the criteria for all the different quadrants. For example, although BEC tends to produce commodity products with established technologies, a few plants are manufacturing more advanced and unique products by employing digital technologies and could be positioned in the upper-right quadrant. Moreover, the overview is an aggregation of all technologies for each company. The individual maturity of different technologies was discussed in the within-case studies (chapter 4). In the next section (5.2), technology utilization will be explained in closer detail regarding the impact on IMNs.

5.2 Impact of digital technologies on IMN configuration

Whereas the previous section presented the various levels of application of digital technologies by the case companies, the subsequent chapter will discuss which of these technologies have an overall impact on manufacturing networks and their related elements. In fact, IMNs are grown structures with individual site histories and typically different technology setups. Although some technologies are homogenous at one site, an IMN typically shows heterogeneous usage of technologies as technologies, products and manufacturing processes have different life cycles (Gölzer, Simon, Cato, & Amberg, 2015, p. 193). For instance, CAC implemented different models of smart robots, as each plant has a favorable technology provider. The same is true for different IT, ERP or MES systems at various plants of ASC, BEC or MTC. Especially IT and related systems have grown over decades and demand large investments for standardization (O'Donovan, Leahy, Bruton, & O'Sullivan, 2015a, p. 6). Additionally, companies operating plants in high-wage and low-cost countries tend to use different technologies. For example, the level of connectivity and automation varies across sites at HAC, MTC, EEC, and CAC. Hansen & Serin (1997) noticed that lower competences and low technologies are typical for less developed countries. Liebeck, Meyer, & Abele (2008, p. 193) add "companies – with few exceptions – should consider at least two different sets of production technology: one for capital intensive production in high-cost countries and one for flexible, simple, labor-intensive production in LCC [low-cost countries]".

The following technologies are implemented by the case companies at different sites with different objectives and approaches. Nonetheless, they are recognized as having an impact on plant roles and manufacturing network configuration now or in the future.

5.2.1 Smart robotics and automation solutions for quality and cost improvements

Form the case studies, three main reasons for implementing smart robotics and automation technology are identified. First, it is highly dependent on the type of product, variants and volume. Hence, for using such technologies high product quantities are required. For example, while EEC's front-end plants are highly automated due to the standardized lot sizes, boxes and work pieces in large quantities, back-end sites have less automated processes. Also, it is only economical for BEC, CAC and HAC to automate with smart robotics or automated machines cells, if large volumes of an item are produced. Companies working in a project business (e.g. MTC) cannot benefit from automation due to small or changing product quantities. That explains MTC's low automation levels worldwide. It becomes clear that manufacturing principles (e.g. make-to-stock or make-to-order) and product-specific factors have an impact on technology selection. Therefore, economies of scale are a basic condition for automation activities (Liebeck et al., 2008, p. 198). Collaborative robotics, however, are an exception as this technology can be implemented for manufacturing small lot sizes or single products. Collaborative robotics are predominantly applied in high-wage locations to reduce labor costs. In particular, CAC, BEC and HAC make use of these robots in different operations. The flexible collaborative robots at different sites of ASC enable a safe and fast work execution in assembly. Physically demanding and unfavorable jobs are taken over by these systems. The main advantage of ASC's solution is the user-friendly adjustment to changing conditions without any reprogramming. Elia, Gnoni, & Lanzilotto (2016, p. 189) add that AR solutions make an adaptation even simpler. In general, collaborative robots facilitate a certain degree of automation and combine the benefits of human and automated work. While full automation is most beneficial for repetitive jobs, a human workforce is more flexible and better for changing tasks and situations (Fast-Berglund, Palmkvist, Nyqvist, Ekered, & Åkerman, 2016, p. 176). According to BEC, collaborative robotics are implemented where full automation is not yet possible or implementation is too cost intensive. However, many of HAC's and BEC's processes that are now supported by collaborative robotics will be fully automated within the next 5 to 10 years.

Second, automation technologies such as robotics or automated guided vehicles are implemented in high-wage countries to reduce direct labor cost and substitute blue-collar workers. Smart robots are becoming more cost-efficient in contrast to human labor, are able to perform complex tasks and operate in dynamic work environments (Strange & Zucchella, 2017, p. 177). For example, smart robotics support the automation of the front-end factories at EEC. As these factories are mainly located in high-wage areas, robotics allow a reduction of direct labor costs. Following CAC's vision, high automation is a key enabler to keep production competitive in high-wage locations. Similarly, ASC and HAC intend to push automation levels in Western Europe to 100 percent to eliminate direct labor costs. This finding is in line with De Treville, Ketokivi, & Singhal (2017, p. 2) as the authors claim that manufacturing plants in high-wage locations seek for higher automation levels for cost reduction reasons. As a result, several case companies unlocked savings in direct manufacturing costs and increased productivity levels. Liebeck et al. (2008, p. 208) found that plants in high-wage countries are typically more automated, due to the higher unit costs for the same intensity of technology application compared to low-cost locations. Nonetheless, most case companies do not recognize a reduction of jobs, but an enhancement of overall productivity and competitiveness of higher automated locations. Even if some jobs are eliminated due to automation, it must not be forgotten that precisely this strategy of automation secures other jobs in high-wage countries.

Third, smart robotics and automation technologies have the potential to increase product and process quality levels. Facilities in low-wage countries profit from this aspect. Traditional robots have been implemented to increase flexibility (over inflexible stations), precision and quality (over manual work) (Hänisch, 2017, p. 19; Krafcik, 1988, p. 50) and smart robots are going to improve these operational goals even more. In terms of quality, digital technologies can have a first stage or second stage impact on quality. Both can improve product quality thanks to the reduction of failures or the error rate. For instance, automation and manufacturing technologies have a direct influence on improving process and product quality (first stage). Especially, human made mistakes are eliminated. Robotics and other automation solutions can maintain consistent quality levels (Swink & Nair, 2007, p. 749). As a result, material, failure and service costs can be reduced. In contrast, data analytics do not directly influence product quality, but have an indirect (second stage) impact by identifying trends and quality issues in processes. With the help of AI, predictive maintenance and process monitoring, existing procedures can be improved, and actions taken to boost quality. Such benefits have been reported by several case companies. Hence, BEC, CAC, EEC, and MTC plan to increase automation levels in Eastern Europe and Asian within the next years to improve product and process quality in challenging processes.

All case companies have realized changes of plant roles and network configuration due to the implementation of smart robotics and other automation technologies. For example, EEC's front-end factories are predominantly located in in high-wage countries. Products that require high added-value, manual work or are not automatable are offshored to lower-cost plants. In the case of HAC and MTC, the companies exclusively manufacture their expensive, high-end and complex products in high-wage locations, whereas standard and high volume products are manufactured in lower-wage regions in Eastern Europe or Asia – although automation is more difficult for high-variance products. BEC also produces its simple and affordable (SMART) products primarily in Asia. Complex products are manufactured in high-wage locations and automated partially with the help of collaborative robotics. The main arguments are lack of technical know-how, qualification and capabilities in lower-wage regions. As high-performance machines and technologies require highly qualified personnel, the level and kind of automation needs to be adjusted to the qualification of employees. It becomes clear that the replacement of a blue-collar workers by smart robotics must be evaluated individually and there are more benefits and potentials than pure labor cost savings. With reference to Wu et al. (2016, p. 405), “automation typically comes into the equation for two interrelated reasons: the need to optimize processes […] and a desire to control costs”, which corresponds to the findings from the case companies. Additional factors for deciding about implementing robotics are ramp-up time and ROI (Fast-Berglund et al., 2016, p. 175).

Proposition A: Smart robotics and automation technologies are primarily implemented in high-wage locations to reduce direct labor costs and in low-wage areas to boost quality levels. Hence, the objectives of automation typically differ across locations.

5.2.2 MES for steering and reallocation of activities

MES is implemented as a dashboard and coordination mechanism for the headquarters at ASC and EEC. It allows the collection, analysis and processing of data to steer and control activities across sites. EEC has implemented a MES in all 18 plants for consolidated production, logistics control, quality management, and decision-making. ASC also employs a standardized MES, which is used for automated reporting, collection and analysis of data. The main field of application is intra-logistics. Daily activities can be planned and facilities benchmarked. Hwang (2006, p. 151) adds that “production managers need to have good control over the condition of production equipment at any time and use the real-time data or statistics data of the instruments and tools of the production equipment as the basis for production scheduling and labor allocation”. Thus, those responsible at the case companies are provided with relevant information and can observe each plant directly. By centralizing all manufacturing states, MES is used to coordinate activities within an IMN. For instance, information about workload, technology and worker utilization or demand peaks are shared across locations at HAC. The aim is to smooth overall plant utilization, which is finally achieved by order allocations within an IMN. The other case companies operate similar MES solutions for transparency and management reasons.

Summarizing, all six case companies use MES to steer and coordinate manufacturing network operations. Even though the manufacturing network is not physically altered, plant roles are extended as new responsibility areas arise. Either the headquarters or the *lead* factories receive additional autonomy for developing, distributing and maintaining MES. A MES contributes to the optimization of production processes, which is becoming increasingly relevant for companies in high-wage locations. Thus, an MES can be used for global site management and to secure the competitiveness of single locations (Gerberich, 2011, p. 88). Consequently, the case companies agree that a comprehensive use of MES allows a better realization of plant roles due to enhanced coordination mechanisms.

5.2.3 Augmented reality for enhanced cooperation and responsibility realignment

AR solutions can be used for product and process design, sales, assembly, maintenance, service, or training. The latter have the potential to change plant roles and responsibilities. Although not all case companies employ AR, the interview partners are aware of the potential benefits of this technology. CAC, HAC and EEC use AR for training activities or for supporting employees and service technicians. By using smart glasses, employees receive instructions and information related to their operations directly on a display. It allows a context-adaptive and situation-based assistance of work processes as well as diagnosis of technical problems. Thanks to the real-time provision of information, an employee can better focus on its value-adding activities (Jost, Kirks, Mättig, Sinsel, & Trapp, 2017, p. 161). In addition, HAC uses AR for its showrooms and product presentations. Similar applications were also identified by Elia et al. (2016, p. 188) and Ong, Zhang, Shen, & Nee (2011, p. 661). While most case companies use AR at plant level, CAC and ASC utilize this technology at IMN level. Thereby, AR is a coordination tool to support employees across sites. Experts in the *lead* factories are steering and guiding service technicians and employees worldwide by using data and AR solutions. For example, time savings of up to 75 percent are reported by ASC. Further, costs are saved as multiple business trips become dispensable. EEC's vision is a direct steering and management of factories in the IMN. HAC describes the future of AR in the same way. Especially for training or troubleshooting across sites, AR technology offers huge potentials. The configuration and plant roles are changed due to the reallocation of responsibilities and the establishment of new departments or specialist teams that are steering other employees or locations with the help of AR. Other mobile devices such as tablet devices are also valuable technologies in this context according to MTC.

Nonetheless, AR solutions cannot be rolled-out to all locations. Thus far, several technical issues and safety aspects are limiting the successful exploitation. First, the weight of the glasses it too high to wear them during a full shift, which was mentioned by ASC and CAC. Second, a battery does not last a whole day, which is critical for service technicians who regularly handle orders without the ability to charge the device. Third, data security and privacy have a negative effect. The analysis of data captured by AR allows a consistent tracking and reconstruction of the workers activities. For instance, pause times, movements or other personal information are automatically collected and could be analyzed for performance evaluation of the workers or service technicians. While such a surveillance is less critical in some countries, especially German work councils and laws prevent the usage of AR on a larger scale (e.g. EEC). Finally, some safety aspects of AR have to be dealt with. The extended use of the glasses can lead to discomfort and dizziness.

These and additional issues are discussed in more detail by other authors (e.g. Azuma et al., 2001, p. 43; Krevelen & Poelman, 2010, p. 14; Martínez, Skournetou, Hyppölä, Laukkanen, & Heikkilä, 2014, p. 35; Mekni & Lemieux, 2014, p. 210). Even though several challenges need to be met to fully implement AR, all case companies are aware of the potentials and benefits of AR for their operations and IMNs.

Proposition B: AR solutions and MES are implemented to coordinate, support and steer manufacturing operations within an IMN. AR has the potential to change network configuration and plant roles due to the reallocation of responsibilities and eased operations.

5.2.4 Additive manufacturing for a better exploitation of selected plant roles

ASC, CAC, BEC, and MTC expect changes of manufacturing footprint resulting from AM in the next 10 to 20 years. At CAC, AM technology has advanced from prototyping to small series production. Similarly, ASC has implemented AM in different fields and identified more than 50 promising applications. Hitherto, however, AM has no real impact on plant roles or manufacturing networks. Most case companies expect a high influence after the technologies become mature enough for large product quantities. If high-quality products can be produced with the help of AM, this will change product allocations and maybe whole industries. Especially, *contributor* and *server* sites are expected to provide customer specific products, which would reinforce their strategic site reason (access to markets). MTC's Swiss plants already produce first customized products or individual goods with AM. As long as the customers are willing to pay the high product price, which results from expensive raw materials and post-processing, the company will invest in this technology. In the future, AM is planning to substitute whole processes such as drilling, milling or cutting by forming a product directly from the raw material with adequate material properties and high surface quality. A highly automated one-piece flow production enabled by AM would strengthen the competitive advantage of high-wage sites and conventional machining processes would be transferred to lower-cost sites according to ASC, CAC and MTC.

5.2.5 Additional technologies with effect on IMNs

Besides hardware automation, MTC, EEC, ASC, HAC, and BEC strive for enhanced data automation. An excellent data quality is a basic requirement for translating collected process, machine, market, R&D, or customer data into valuable information. It is the foundation for knowledge creation to understand coherencies or processes. In the future, the next stage will be automated decision-making based on data provided by machines and systems. Being able to predict future events and correlating actions should improve existing processes. First AI implementations at HAC for predictive maintenance solutions offer promising results. Systems guided by AI and automated control are promising for processes and plants. In contrast to other digital technologies, AI, Big Data solutions or machine learning have the potential to affect all sites regardless of location. However, the case companies have not yet got that far.

Furthermore, digital technologies have the potential to reduce transaction costs for communication, collecting information and controlling (Loebbecke & Picot, 2015). Especially, cloud computing has an impact on manufacturing networks. While in the past information was stored decentralized on servers, nowadays data is integrated and stored in a cloud. Those in charge for manufacturing, marketing or sales have real-time access to the centralized stored data, which leads to improved internal processes as well as customer offerings at BEC.

Proposition C: Selected technologies such as AM, AI, Big Data, or cloud solutions have a potential to impact manufacturing networks. However, thus far, these technologies only unlock competitive advantages at plant level as technological readiness is relatively low.

The implementation of digital technologies is not necessarily related to the technological maturity of sites. Thus, even advanced, technological driven and equipped *lead* plants can support other sites. Even if processes in a site are relatively un- or underdeveloped, AR or MES as examples of process-uncritical technologies, could support different operations. Although consistent connectivity and data flow are not possible in this case, such technologies can increase efficiency, transparency, and reduce defectives, as well as improve quality and decision-making – also in low-wage locations. The resulting isolated applications would at least provide a temporary advantage. For example, BEC's technology setups and structures differ across locations, but selected technologies create additional value regardless of the location. The prerequisite is the development of a standardized process or technology in a *lead* factory, which later is slightly modified and adapted to local conditions. The next section will introduce different strategic and implementation approaches of the case companies.

5.3 Strategic management and digitalization approach

The within-case analysis shows that the case companies differ in their strategic management approaches in the context of digitalization activities. Table 20 outlines the main differences and similarities concerning hierarchical participation and dominating approaches. With reference to Kim, Sting, & Loch (2014, p. 466), top-down and bottom-up management are "based on who initiated the action and how it was initiated". Top-down management comprises all decisions and actions steered and initiated by top management functions. In contrast, bottom-up management describes the introduction and implementation of ideas and solutions by shop floor employees, lower or middle management without instructions or orders by the top management.

Table 20: Strategic management approach for digitalization activities (own illustration)

	Machine tool company (MTC)	Building equipment company (BEC)	Automotive supply company (ASC)	Control & automation company (CAC)	Electronic equipment company (EEC)	Home appliances company (HAC)
Top-down management	●	●	●	●	●	●
Bottom-up management		●	●	●	●	
Explorative approach		●	(●)	●	●	●
Strategic approach	●	●	●	●	●	

Note: The brackets symbolize that the case company has "finished" its explorative approach.

The top-down approach is widely documented in literature. Various authors investigated this organizational style in different fields such as manufacturing strategy development (e.g. Bendoly et al., 2007; J. S. Kim & Arnold, 1996; Ward & Duray, 2000). However, several researchers emphasize that bottom-up approaches are more realistic in real settings (e.g. Slack & Lewis, 2011). For example, Womack, Jones, & Roos (1991) and Kim et al. (2014), argue that bottom-up management is important for employee involvement, learning and continuous improvement.

All case companies apply a top-down management and most a bottom-up approach. As seen in the within-case analyses, the combination of both offers several advantages according to the companies. For instance, corporate management at CAC defines the big picture and vision. This vision is further detailed and individual strategies for each factory derived. At the same time, new ideas, business cases or potential improvement levers are provided bottom-up. BEC, ASC and EEC manage their digitalization in a similar way. In fact, projects or solutions are initiated by shop floor employees as they have the required specific know-how. Top management supports and coordinates these activities by setting the overall direction and defining appropriate measures and strategic goals. In general, top management engagement is essential in four ways. First, required financial, technological and human resources can be approved and steered without loss of control. Second, it allows a sustained, learning-based and long-term development of processes, structures and goals. Third, top management defines the mechanism to distribute and transfer the solutions implemented on shop floor. The case analysis showed various solutions (e.g. *lead* factory, transfer unit, bilateral exchange). Moreover, the case companies show that the approaches for distributing digital technologies in IMNs differ. While ASC implements technologies equally and simultaneously at all sites that produce a specific product category, CAC introduces new technologies first in their home country before they distribute it to other regions. Even more, it is rarely the case that CAC decides that all plants should adopt the same technologies. BEC puts less focus on digitalization in lower-wage countries. If digital technologies are implemented, the aim is to speed up processes, improve quality or relieve employees. MTC manages its transfer of digital technologies even more restrictively as some technologies are only implemented after becoming outdated in the home location to protect knowledge diffusion. However, this strategy might lead to unproductive and inefficient processes at a foreign site. A simultaneous transfer (e.g. ASC) is only possible for similar products and processes, but learning curve effects are missing. The latter is one of the main reasons for CAC to roll-out digital technologies step by step. This phenomenon is similar to the findings of Keller & Chinta (1990, p. 37) who define these approaches as *parallel*, *delayed* and *sequential* introduction.

The fourth top management engagement area is standardization. Only top management can guide and enforce standardization activities. For instance, MTC has standardized tools and controlled processes in place for most processes and decisions to ensure a homogeneous implementation. Otherwise, each site would probably define its own interfaces and systems, which would later result in redundancies and incompatibility. Therefore, coordination of knowledge, communication and commitment are vital, which is in line with the conclusions of Kezar & Eckel (2002).

Whereas ASC, BEC, CAC, and EEC apply top-down and bottom-up management, MTC and HAC primarily focus on top-down approaches. Although the companies do not report critical issues, this procedure can cause some problems. If people on the shop floor cannot sufficiently participate in decision-making, the employees' acceptance of procedures and their commitment will deteriorate. In the worst case, this might lead to serious resistance. Additionally, it is more than likely that the wrong focus will be set. Without involving shop floor experts, the utility and value of new shop floor solutions is unpredictable. In cooperation with shop floor employees, top management should discuss and derive distinct measures that have potential long-term benefits and are widely accepted by workers.

Another factor influencing management approach is the ownership relationship. HAC and CAC are family-owned businesses, which is a crucial factor regarding digitalization for two reasons. On the one hand, the companies can make faster and long-term oriented decisions as they are not driven by short-term shareholder value. In this regard Morris et al. (1997, p. 387) argue, “businesses that are family-controlled frequently have a more centralized decision-making process and control systems that are less formalized”. In contrast, larger organizations (e.g. ASC, EEC) often suffer from long decision-making procedures as numerous stakeholders and hierarchical levels are involved in the decision process. On the other hand, the probability of offshoring activities is less likely. Having a long tradition and reputation in combination with the labels “made in Germany (or Switzerland)” are often indispensable factors or unique selling points for family-owned companies.

Finally, the combination of both top-down and bottom-up approaches limits wrong decision-making and employees’ resistance. Grover et al. (1995, p. 114) confirm that “rigid hierarchical structures within the organization inhibit change behavior” and thus, a systematic involvement of all related internal stakeholders accelerates and enhances implementation and decision processes regarding digital technologies. The benefit of including external stakeholders is discussed in chapter 5.4. Although most case companies follow a top-down and bottom-up management approach, they investigate and manage digital technologies differently. This may in certain circumstances be explained by the fact that the companies apply a strategic approach, which demands a long-term planning attitude, an explorative procedure (trial-and-error principle) or a combination of both.

A strategic approach is typically systematic, sustained and organizationally grounded. It is a holistic method across departmental or functional boundaries and typically outlined by top management. Whereas all case companies apply such an approach, MTC is the only company that exclusively concentrates on strategic developments. MTC has created a department which is responsible for all digitalization activities. In contrast to other case companies, use or business cases are normally not promoted or implemented by MTC. Instead, MTC strategically defines required solutions or business cases and obtains them externally from other companies or acquires a specific provider (e.g. AM or software company).

Most case companies tend to combine the advantages of strategic and explorative approaches. Explorative approaches are based on a trial-and-error principle. They have an iterative nature and foster organizational learning (Sosna, Trevinyo-Rodríguez, & Velamuri, 2010, p. 386). Explorative attempts are often cheaper, small-scaled and have a short-time horizon at lower risks compared to strategic approaches. Moreover, an explorative approach accelerates decision-making, development and implementation. For instance, BEC and EEC have established expert groups that test new technologies according to their long-term visions and strategies. Especially, BEC's operating model provides guidance and sets the direction for digitalization activities. Although digitalization activities are decentralized at EEC, top management has strategically defined the boundaries and focus areas and, within these areas, explorative projects are conducted to implement and learn about digital technologies. Similarly, HAC has a strategic and explorative setup regarding digitalization. Even though each plant can do investments individually, an overall roadmap and predefined ROI are required for each digitalization activity. The decentralized organization of HAC has allowed the company to gain various experiences and knowledge, but it has also led to redundancies, unstructured processes, and technology developments. Some form of organizational restructuring should solve this concern.

CAC has a few lighthouse projects, which were derived strategically. These projects cover different topics such as automation, collaborative robotics, AI or data analytics and are seen as pillars of CAC's business. The strong belief that these new technologies will result in higher productivity and quality as well as lower costs encourages CAC. In close cooperation of R&D, manufacturing and IT management, projects and technologies are evaluated systematically. On the other hand, CAC describes itself as an explorative company that frequently invests in upcoming technologies and ideas, which are not rooted in strategy. An example is CAC's health-promoting lighting system. Such lighting systems imitate the sun light and change the brightness parameter during a three-shift working day. Depending on the shift, employees can enjoy "natural lighting", which corresponds to the biorhythms of the workers. Although the company is not aware of the actual benefits and long-term effect, CAC established this system in most factory buildings. Longitudinal studies about the impact on employees' health and welfare are expected to show first results in 5 to 7 years. Hence, a defined business case or ROI is not always mandatory to push such projects. Since this is just one of many examples, CAC is generally considered to be more explorative compared to other manufacturing companies.

In contrast, ASC has finished its strategic phase. After completing more than 50 explorative projects, the company decided to align all other on-going and new projects to a strategic plan. ASC now implements and invests in selected business cases and digital technologies on a larger scale. Nonetheless, the case company's informants emphasize that the explorative phase was essential to accelerate decisions and become successful in managing today's digital technologies.

To sum up, the combination of strategic and explorative approaches allows a long-term and learning-based development of digital technologies and digitalization projects to create returns today and in the future. Most case companies make use of both approaches. An exploratory phase is often seen as a starting point for digitalization activities, which are later strategically clustered to develop long-term roadmaps or scenarios.

Proposition D: By linking top-down and bottom-up management, companies can enhance employees' loyalty and reduce the likelihood of setting the wrong focus. In combination with explorative and strategic approaches, an accelerated and sustained implementation of digital technologies becomes feasible.

Apart from the management of digital technologies and digitalization approaches, the strategic management of the manufacturing networks varies between the case companies. For example, ASC, BEC and MTC have strategically developed their IMNs and plant roles. The plant roles are explicitly communicated, and systematic guidelines and tools support the supervision of the existing IMNs. Nonetheless, the plant-technology-competence framework identified several redundancies and unwanted developments at MTC. Therefore, even a systematic and strategic alignment of an IMN cannot avoid all weak spots. Similarly, ASC faces the challenge of satisfying the expansion attempts of its highly innovative plants and to limit the growing internal competition. As ASC's plants are managed as profit centers, they invest in new solutions without any permission from a central function. Consequently, many redundancies and double functions have emerged. Hence, the relatively high degree of freedom led to undesired developments at ASC. BEC has also made use of a systematic approach to set up its entire manufacturing network by scaling it down to nine sites. However, plant role determination was not part of the strategic approach. But in direct comparison to ASC and MTC, BEC's strategic management of digital technologies and network activities are a better fit.

In contrast, CAC's, EEC's and HAC's network management approaches are rather unstructured. Even though CAC makes use of different site roles, these roles are not systematically set up. Especially the overlapping responsibilities regarding technology and product *lead* factories make it difficult to unlock real benefits. In addition, each plant is allowed to invest and focus on digitalization activities individually. This kind of decentralized decision-making is a major reason for redundancies at CAC, because the central function (headquarter) has not yet been able to better organize such activities.

Last, EEC and HAC do not make use of plant role models or a structured IMN design. Although some sites have evolved "naturally", these roles are not strategically arranged or even communicated, which makes it difficult to share knowledge and other resources.

Moreover, digitalization is managed on a decentralized basis at EEC and HAC. As most plants operate autonomously, they partially developed in different direction and have dissimilar technological setups and histories. As technologies and know-how are typically transferred bilaterally from one plant to another at HAC, redundancies and double work are unavoidable. In the future, digitalization activities should be clearly assigned to specific *lead* factories or new CoE at HAC to limit the emergence of redundancies and extra work for standardization. Hence, EEC and HAC strive for a harmonization of their IMN activities.

To sum up, companies that have no real network management and do not systematically define plant roles typically have many isolated digitalization projects and activities that are overlapping and not interlinked. The resulting redundancies result in higher costs and waste of resources. However, the case of BEC shows that both the management of digitalization and IMN activities must fit. Optimizing only one of the topics is not target-aimed. In this regard, the plant-technology-competence framework (figure 12) can support operation managers to coordinate digital technology activities and link them to the manufacturing network. This is even more promising in the case of unplanned IMNs. Finally, from the cross-case analysis it becomes clear that the management of IMNs – with and without digitalization attempts – requires continuous adaptations and agility.

5.4 Location factors and geographical levers for digitalization activities

All case companies have structured their IMNs according to the location factors *proximity to market, access to low-cost production* and *access to skills and knowledge*. These are identical with Ferdows' (1997b) three main strategic reasons for plant locations and proves their applicability. Although only MTC and ASC have strategically and systematically derived their site roles, selected roles pre-defined by Ferdows (1997b) can be found in each IMN. In addition, there is a clear tendency for individual plant roles and locations. First, all six case companies mention that their high skilled plants with access to knowledge, research institutions and qualified employees are typically located in high-wage locations, with some exceptions. Hitherto, the qualification and technical background of employees seems more advanced in Western European (or Northern American) countries than in Asia or Eastern Europe. For example, other researchers found that a significant and positive relationship exists between the gross domestic product and the digitalization index of countries. Further, there is a significant and positive relationship regarding the level of education (Billon, Lera-Lopez, & Marco, 2010, p. 64). Equally, Kinkel & Maloca (2009, p. 159) identified the lack of qualified employees in foreign locations as a hurdle to fulfilling manufacturing and R&D tasks. Therefore, all case companies have at minimum one *lead* factory positioned in Western Europe. For instance, ASC's five *lead* plants are exclusively located in Germany and EEC's "natural" *lead* factory for front-end plants is positioned in Germany, too. However, access to know-how and qualified employees is also slowly developing as a success factor in Asia. When talking about Asia we must distinguish between highly developed countries such as South Korea, Singapore or Japan, less developed nations (e.g. India, Vietnam) and China. According to the case companies, the location factors in Singapore or Japan are comparable to conditions of Western European sites. Less developed countries are seen as low-cost manufacturing regions in Asia, while China is an exception in various respects. It has a growing and dynamic economy and due to its huge population it is a valuable market for all case companies – except for HAC. Today, China is the largest FDI recipient and second largest economy (Kinkel et al., 2014, p. 176). Further, within the next 5 to 10 years, especially China could reach the knowledge level of the Western European countries. BEC and EEC have already one *lead* factory each in China. Moreover, ASC's plants in less developed countries are becoming increasingly advanced in different fields. Likewise, Meijboom & Vos (1997) identified in their study that plants in low-cost countries, which were initially set up because of cost objectives, are nowadays potential sources of knowledge and learning.

The second major location factor for plant roles is the proximity to customers and markets. In particular, customer proximity and delivery time play an essential role. For instance, for a certain assortment (about 20 percent in total) of product types that are available in thousands of variants, a location close to the customer is inevitable for BEC to provide customized and on-time solutions. This "time-based competition" has a critical impact on a company's footprint design (Kristianto et al., 2017, p. 607). CAC emphasizes that China is the most dominating and remunerative market and, consequently, the company establishes its largest factory in China. Additionally, ASC typically follows its customers and therefore, plant location decisions are dependent on customers. In fact, ASC sees its sites in China as important for market access and due to rising labor costs as less pertinent for low-cost production. It becomes clear that China will remain the most relevant market worldwide in terms of access to markets. Finally, there is a clear tendency that most case companies serve their customers local-for-local. Holweg (2005, p. 605) describes this kind of responsiveness as "the ability to react purposefully and within an appropriate time-scale to customer demand or changes in the marketplace". In contrast, as EEC's products are light, small and easy to ship, the Chinese markets could be served from other regions. Therefore, customer proximity is less pertinent for EEC. In the case of HAC, approximately 80 percent of advanced products are sold in Europe and the markets in Asia and other regions play a minor role. If customer segments changed, HAC would adapt its manufacturing footprint accordingly to address new customer groups, but that seems less probable from today's perspective. However, the proximity to markets by selling products local-for-local in Europe is an indispensable factor for location decisions for HAC.

Third, access to low-cost production is another important criterion for plant locations, which was mentioned by the case companies. For example, ASC, CAC, HAC, EEC, and BEC have located their low-cost sites in Eastern Europe. Eastern Europe is only a small market and accordingly serves as an extended workbench for Western European sites. Labor cost, regulatory expenditures and partly energy cost are significantly lower in several Eastern European countries than in Western Europe. Some other low-cost plants are located in India or Southeast Asia. Only EEC emphasizes that its Chinese sites are also focusing on low-cost advantages, while the other case companies see their Chinese sites primarily important for access to market. However, for CAC and MTC are the manufacturing cost for their products almost the same in China and Germany (or Switzerland), when logistics cost and import tax are neglected. For some products, labor cost share only accounts for less than six percent of the overall product price in the case of MTC. Besides, labor costs are rising by 15 to 20 percent each year in China (Tate, Ellram, Schoenherr, & Petersen, 2014, p. 383). Thus, if customer proximity and low-cost manufacturing play a minor role, there are fewer prevailing reasons to produce in foreign countries that are far from the knowledge hubs (in Western Europe). Furthermore, CAC and HAC refer to the distance to China, which makes low-cost manufacturing in Eastern Europe even more attractive compared to remote (Asian) locations. The accruing tax and logistics costs have a negative influence when exporting from Asia to Western Europe. Instead, all companies except HAC and EEC mentioned that Asian sites primarily facilitate proximity to markets, although these sites were built up as low-cost sites in the past. As a result, the case companies export less from China to Europe and vice versa. In particular, a total or landed cost analysis can provide rich information about the actual costs at a foreign site (cf. Eloranta, Blomqvist, & Laiho, 2014).

Proposition E: While access to skills and qualified labor typically exists in Western Europe, access to low-cost production factors is mostly related to Eastern Europe. China's initial advantage of low labor cost is (gradually) being replaced by access to markets and customers.

For all case companies access to qualified employees and know-how is most relevant for implementing digital technologies. Low-cost and access to markets were not mentioned by the case companies to be vital for utilizing such technologies. Although access to markets is one of the main arguments for today's location decisions (Laiho & Blomqvist, 2014, p. 216), it is less important in the context of digital technologies. However, the advantages of low-wages often cannot be addressed, because lower-wage regions have "primary weaknesses of infrastructure, legal systems, and regulated economies" (Prasad & Babbar, 2000, p. 222). Additional factors become rather essential. This is consistent with Turkulainen & Blomqvist (2010, p. 11) who emphasize that site reasons are typically more complex. In this case, supplier support, infrastructure, culture, reputation, image, and technological experiences are frequently mentioned by the case companies for being relevant in the context of digital technologies. The latter is strongly dependent on the individual plant role.

- Supplier and technology provider support: External cooperation is crucial for developing and implementing digital technologies. The entire case sample collaborates with external stakeholders in the context of digitalization. Suppliers and technology providers are most important, because they typically provide joint research, full solutions or support. As development activities are often regarded as time-consuming and resource-intensive, the cooperation with such stakeholders can accelerate R&D and innovation processes (Benninghaus, Budde, et al., 2018). However, it is not enough that a provider just sets up a machine in a location. Although a provider does not necessarily have to be on-site, they need to offer reasonable local service. In fact, this requirement cannot be fulfilled in each country. Less developed areas in India or very exposed plants in other world regions have limited access to technologies or technological support. For CAC, one main insight was that it is not reasonable to define a worldwide machine and technology standard. If possible, CAC chooses local providers, because only the exceptionally large companies can urge their providers to offer service everywhere in the world. In this regard, CAC's and MTC's impact on suppliers and providers is not big enough. They are relatively small players due to their limited volumes, large variety of products and have little negotiation power. Larger companies such as ASC or EEC can convince their suppliers and technology providers to arrange full service support as their negotiation power and sales volumes are higher. Supplier dependency is a critical factor for BEC, EEC, ASC, and MTC to strengthen their innovative position. Their main machine suppliers are located in Western Europe (i.e. Germany and Switzerland) or North America. Therefore, the access is (still) better in high-wage locations (Stolle et al., 2008, p. 328). Phene & Almeida (2003) also found that knowledge exchange and sourcing related to technology are not limited to a firm's own manufacturing network. Instead, regional networks and linkages with other companies enhance technological competences. Thus, local embeddedness and the relation to suppliers or other firms are "a crucial source of knowledge […] and impact directly on the development of its technological capabilities" (Tseng & Chen, 2014, p. 375). As cooperation is crucial for digital technology development, factories in some world regions such as Asia and Eastern Europe do not often contribute to digitalization activities (cf. HAC, MTC).

- Infrastructure: A critical factor for implementing digital technologies is the local infrastructure (Morkos et al., 2012, p. 101). In fact, infrastructure has a significant impact on location decisions for companies (Munnell, 1990, p. 22) and infrastructural differences are relocation drivers (P. Martin & Rogers, 1995, p. 349). This effect becomes even more significant in the context of digital technologies. Hard and ICT related infrastructure are of utmost importance. While the hard infrastructure includes railways, roads, energy, water, or waste supply, ICT related infrastructure comprises access to internet, networks, servers, or data storage (Anthopoulos, 2017, p. 35). Both have a significant impact on the location and plant roles as some digital technologies can only be utilized if both kinds of infrastructures are available. According to Kache & Seuring (2017, p. 30), "a lack of powerful infrastructure, subsuming technology, processes, and people, is a key challenge for the processing of real-time information in a digital business environment". For example, EEC's processes are very demanding regarding infrastructure. High connectivity rates and levels of automation require satisfying ICT related infrastructures in all plants. Even for MTC's technologies and processes a certain infrastructure is essential. Although the basic infrastructure such as WLAN is at a satisfying level in all locations, even more advanced infrastructure conditions are required for specific applications. For that reason, MTC is working on high-speed data systems in Switzerland in close cooperation with technology providers. In other manufacturing locations, the infrastructure will be adjusted accordingly depending on the level of functionality and connectivity needed. However, all case companies mentioned that the required infrastructure exists in their current manufacturing locations worldwide. As hard and ICT related infrastructure are exclusion criteria for setting up a location, the companies do not report problems. High-wage countries in general tend to have a superior overall infrastructure (Martí, Puertas, & García, 2014, p. 2983; Prasad & Babbar, 2000, p. 212). Furthermore, most areas in Eastern Europe as well as the metropolitan regions in China have a very advanced infrastructure. Some countries are even developing faster in selected infrastructure topics (e.g. internet speed) than high-wage locations such as Germany or Switzerland (Park, Im, & Noh, 2016, p. 218). An exception are conditions in India where several case companies operate facilities. Sensitive power supply and street conditions are often reported as serious issues in India. For that reason, ASC and BEC implement and invest in failure systems, redundancies and an independent power supply to maintain self-sufficient infrastructure within the own factories. Therefore, infrastructure quality depends on countries or even more on selected regions. In conclusion, Munnell (1990, p. 26) confirms that infrastructure has a positive impact on a company's investments and output, but this factor becomes less relevant for areas where the case companies (currently) operate their factories.

- Culture: Especially EEC reports culture to be another relevant factor for operating digital technologies. It comprises, among others, behavior patterns, values, standards, and artefacts (Wien & Franzke, 2014, p. 36). Similar to the findings of O'Donovan et al. (2015a, p. 7), the representatives of ASC mention employee motivation and commitment as crucial elements of their company culture. These aspects have a major influence on the success of implementing digital technologies. Hence, there is a need to train and educate employees to allow them to understand and operate new (digital) technologies (Hofmann & Ruesch, 2017, p. 33). Discussions in the context of technology acceptance models (e.g. Davis, 1986; Venkatesh & Davis, 2000) could extend this perspective. It is important to understand that plants build their own specific knowledge and competitive advantage. Thereby, culture is an unique factor, which varies along the location of plants (Demeter & Szász, 2014, p. 31).
- Technological experience: The technological skills and knowledge are widely path dependent as the company's past capabilities and experience characterize its future technology-based decisions (Arthur, Ermoliev, & Kaniovski, 1987; Nelson & Winter, 1982; Phene & Almeida, 2003; Teece et al., 1997). It implies that a site's past experience is the foundation for future technological changes and choices (Phene & Almeida, 2003, p. 351). Technical capabilities as well as familiarity with methods and technologies are prerequisites (E. B. Grant & Gregory, 1997, p. 999). This fact explains the development of *lead* factories. For instance, the case of EEC confirms this argumentation as EEC's *lead* factories have naturally evolved due to their long experience regarding selected technologies. Thus, digital technologies are often initially tested and implemented in such *lead* sites. Other plants within the IMN can benefit from the experiences of the *lead* factories. Cheng et al. (2016, p.

550) found that "a plant, belonging to such a manufacturing network, is able to learn more about technology, customers, products or processes from other plants than it can learn by itself". As more developed sites in high-wage locations have a longer history, they were able to gather and enrich their knowledge base concerning technologies and processes better than less developed sites (Gupta & Govindarajan, 2000; Mudambi, 2008).

- Reputation and image: Thanks to better quality control, production systems, transparent monitoring, shorter feedback time, automation technologies, and data analytics, location has less effect on final product quality. However, most case companies still report varying quality levels across plants, which ultimately is represented by the multitude of discussions and literature regarding reasons for relocation (e.g. Dachs & Kinkel, 2013; Di Mauro, Fratocchi, Orzes, & Sartor, 2018; Gray et al., 2017; Stentoft, Olhager, Heikkilä, & Thoms, 2016). Although customers cannot easily identify quality differences, some customers of ASC, CAC HAC, and MTC prefer products manufactured in high-wage locations with an implicit quality promise (e.g. made in Switzerland or Germany). For MTC and HAC these labels are especially important and a unique selling point. Consequently, the consumers are willing to pay an extra price for products in HAC's B2C market. MTC adds that the reputation for high-end products made in Asia is less persuasive compared to high-wage regions. In contrast, the reputation of "made in Germany (or Switzerland)" is less important for CAC or EEC.

In addition to the identified criteria, BEC, MTC, EEC, and ASC mention additional location factors for implementing digital technologies. These are working processes, an established lean concept and employee commitment.

Proposition F: Digital technologies are first implemented in plants that have access to know-how and qualified employees. Other factors such as supplier support, infrastructure, technology experience, reputation, or culture foster an implementation.

Most location factors such as qualified employees, knowledge, long history and experience, technology utilization, developed infrastructures, and access to suppliers are addressed in many ways in high-wage countries. Hence, a clear consequence for high-wage locations can be the expansion of capacities based on the advantages of digital technologies. CAC, EEC and MTC have recently built or are building a new site either in Germany, Austria or Switzerland. In the case of MTC, the building of a new plant consolidates all activities of initially three Swiss plants in one location to generate synergies and cost savings. MTC has a long history in the machine tools business in

Switzerland and the profound expertise and product know-how is only available in Switzerland. Similarly, for all three case companies the proximity to know-how and qualified employees is the most important factor to build a factory in a high-wage country. On the one hand, the education systems in Western Europe allow a dedicated education of junior employees. On the other hand, several research and industry clusters in Germany and Switzerland offer the opportunity to hire additional experts from different industries. To attract qualified employees and talents, the new sites typically have a modern design and latest technologies.

A new plant can be established by different measures such as a green-field approach, joint ventures or acquisitions of plants (Cavanagh & Freeman, 2012, p. 603). In fact, as EEC's electronics industry is very capital intensive, older factories are consequently renewed or upgraded. For that reason, EEC's new factory was built on the grounds of an older chip factory. In contrast, CAC and MTC used a green-field approach to establish their new facilities in Germany respectively Switzerland. Their new plants are fully dedicated to digital technologies and smart products. Consequently, CAC's new site became a *lead* factory for new products and technologies. Although *lead* factories are regularly not established on a green-field (Deflorin, Dietl, & Scherrer-Rathje, 2010, p. 3), CAC's new plant developed and extended its competences in a very short time.

Internally CAC, EEC and MTC see their new sites as an impulse or forerunner for the production (lines) of the future. When building their new plant in Germany, the main location criteria for CAC were access to qualified employees and the ability to transfer knowledge, technologies and processes from other plants there. This plant does not only perform production activities, it also serves as a R&D and global knowledge hub for pneumatic and control products. Further, the new plant is also a *lead* factory for different conventional production technologies in terms of forming, cutting, joining, and coating as well as for supporting technologies such as AR, mobile devices, M2M, and collaborative robotics. EEC also assigned such responsibility areas to its new plant in Austria. As these technologies are not only developed, but also implemented, the companies were able to increase productivity levels in the new sites. For example, collaborative robots enhanced ergonomically challenging processes. Automatic data collection enabled transparency as well as decision-making or AR improved coordination within the factory and across locations at CAC. A precondition for the success of the new sites are working lean principles including optimal material flow and reduced waste. For instance, the whole production process of a specific product line at CAC, which spread across several plants was reduced to 120 meters in the new optimized manufacturing plant layout.

Furthermore, EEC, CAC and MTC report additional objectives for their decisions to manufacture in high-wage countries. On the one hand, they use or plan to use their new facilities as a kind of marketing instrument and promotion tool. For example, in the case of CAC, the new plant receives publicity for the technologically advanced processes, the energy-saving and emission reduced building, the state-of-the-art energy recovery as well as the human centric approach (e.g. health-promoting lighting systems, learning workshop, ergonomic workplaces). Public visitors or customers are invited to see EEC's or CAC's products working in a real setting as well as the innovative solutions used in the factories. They see what level of automation and digitalization is possible and how the new enhanced processes work. Visitors learn about and in best case procure CAC's products, because of the (impressive) demonstration in the field. Moreover, public events with governmental representatives and several awards underline the usability of EEC's and CAC's products in real settings. Both increased sales and image improvements are intended. Last, the three case companies received various subsidies and tax benefits from local governments. Both tax break and financial benefits supported the decisions to build their new factories in high-wage locations. Managers at EEC emphasized that their manufacturing footprint has been highly influenced by subsidies in Germany and Austria for the last 50 years.

In summary, a consequence for high-wage locations might be additional investments, as digital technologies enable an efficient manufacturing with reduced direct labor costs. For instance, EEC, MTC, CAC, and ASC regularly invest in high-wage locations and expand capacities, because their markets are growing. The access to knowledge, public image improvements and subsidies are supplementary reasons for considering engagement in high-wage locations. In contrast, BEC does not consider reshoring manufacturing activities or extending capacities in high-wage locations due to its adequate production capacities in Western Europe. Similarly, ASC would not relocate manufacturing activities to high-wage countries only because technological advancements allow a significant improvement of processes and efficiency, as plant decisions are related to customer proximity. Thus, digitalization is not the main driver for relocating manufacturing operations or building new plants in high-wage areas, but customer and market dynamics could enforce a relocation to high-wage locations. However, digital technologies are critical enablers for the efficient and innovative production in high-wage regions in combination with qualified employees. They are a job retention measure.

Proposition G: Digital technologies are not drivers, but enablers for efficient manufacturing operations in high-wage countries. As most required location factors (i.e. access to knowledge and qualified employees) for a successful application of digital *technologies are available, ultimate consequences might be the establishment of new manufacturing facilities or capacity expansion in high-wage locations.*

5.5 Focused plant roles and responsibilities

In the context of digitalization, several plant roles benefit from the utilization of digital technologies. Although plant roles are often not strategically derived and managed, all case companies operate one or more *lead* factories. EEC has “natural” *lead* factories with a temporary character that are not officially communicated. The natural *lead* sites only exist as long as they are leading regarding one topic area. At BEC, *lead* factories have the leadership for a certain product type and all related processes. CAC’s *lead* factories have either a product focus or a technology focus. Even though all case companies operate (implicit) *lead* factories, the concept is more eligible under certain circumstances (Deflorin et al., 2012, p. 530). On the one hand, a large number of plants in an IMN facilitates the *lead* concept to improve coordination mechanisms and knowledge transfer. Ferdows (2006) distinguishes here between codified (simple to transfer) and tactic knowledge (difficult to transfer). If such tactic knowledge were to be shared, various ICT solutions such as ERP could support the transfer of knowledge (von Krogh et al., 2018, p. 54). On the other hand, the reduced specialization of sites and processes as well as low adaptation costs unlock advantages. The latter is consequently pursued by MTC that hosts identical processes in different world regions.

In general, *lead* plants balance centralization and decentralization advantages. Critical resources and capabilities are pooled at a *lead* factory, whereas all other resources and activities are decentralized in local plants (Tykal, 2009). *Lead* factories have a support and not a control function. They are not ruling other sites but support them in two ways: pull and push. For example, the Indian manufacturing sites request support or resources from the *lead* factories (pull principle), while the Swiss *lead* factories transfer their knowledge or resources in form of a push principle. This avoids knowledge erosion and simplifies coordination as everything is steered by a single source. For example, at ASC, all sites worldwide have access to information and knowledge. Other case companies (e.g. HAC, MTC) decided to limit the knowledge and know-how diffusion by concentrating some key processes and technologies in their high-wage locations. Thus, strategic components such as electronics are manufactured exclusively in high-wage areas. Patents, especially those which are only enforceable in some regions, are another reason for local manufacturing. While all sites should concentrate on their competences and manufacturing activities, the case company’s *lead* factories leverage knowledge across sites. Nonetheless, *lead* factories typically operate a sophisticated machine park and are able to produce products. The machines and systems are commonly the newest or most advanced throughout the whole IMN.

Additionally, *lead* factories have a high autonomy as well as more specialists and resources compared to other plants in an IMN. The autonomy of a *lead* factory depends more on the organizational structures and less on its bundle of competences. Moreover, *lead* factories at ASC, BEC, CAC, and MTC have various competence and responsibility areas. Either a *lead* factory hosts R&D departments as seen in the case studies or it functions as an “intermediary” between R&D locations and manufacturing sites in an IMN (Deflorin et al., 2012, p. 521). Besides R&D, process and product improvements, *lead* factories take responsibility for training, employee qualification and job rotation, support, troubleshooting, continuous improvement, organization of expert workshops and exchange, best practice and knowledge sharing, product allocations, supplier selection and development, design of product life cycle, safety, maintenance, or standardization. In addition, process ramp-up, technology development, testing, and implementation in the context of digitalization are main tasks of ASC’s, BEC’s, CAC’s, and MTC’s *lead* factories. High capacity for innovating new products, utilizing technologies and improving processes are central competences of *lead* sites (Mediavilla et al., 2014, p. 94). A *lead* factory is also the point of contact in case of inquiry or for troubleshooting at other sites dealing with similar technologies. Depending on the digital technology class, these responsibilities are more or less evident. Hence, *lead* factories serve as know-how hubs. For example, the other plants of MTC are copying the solutions developed by the *lead* plant, because the processes in all sub-networks are rather identical for a specific type of product. Consequently, *lead* factories “serve as partners of headquarters in building strategic capabilities” (Ferdows, 1989, p. 11). In contrast, HAC’s independent plants have different maturity levels and systems and cannot take over such technologies effortlessly.

Technology transfer is an important capability of a *lead* site. All interview partners emphasized the importance of successful technology transfer from the *lead* factory to other plants within the IMN. As soon as a technology and the associated process run stable, it is transferred by a *lead* factory to other locations. Even though other plants benefit equally from digital technologies after a roll-out, *lead* factories and accordingly high-wage locations need to continuously be the forerunners to reduce internal and external competition. Such a systematic sharing of process innovations and technologies results in higher operational performance (von Krogh et al., 2018, p. 54). The subsequent procedure follows the input of the case companies and is partly enriched by the work of Thomas et al. (2008). In fact, as other researchers identified comparable procedures for technology transfer within intra- and inter-manufacturing networks (e.g. Bruun & Mefford, 1996; C. S. Galbraith, 1990; E. B. Grant & Gregory, 1997; Keller & Chinta, 1990; Stock & Tatikonda, 2000), this extract will just provide a brief overview of the findings. Appendix K summarizes the approach, which is used in a similar form by ASC, CAC, MTC, and BEC. First, in a pre-selection, a technology for transfer must be nominated. The selected technology needs to fit the company's manufacturing strategy and a process enhancement should be possible. Afterwards, organizational factors and competences are analyzed. For example, an under-utilized technology, cultural divergences, missing capabilities and commitment of the employees are often factors resulting in a failure of transfer. Instead, appropriateness, robustness and transferability of the technology need to be evaluated (E. B. Grant & Gregory, 1997). On the one hand, appropriateness and robustness describe how easily a digital technology can be transferred across locations. A robust technology can be distributed to any other site and fits local conditions without any adaptations. On the other hand, transferability considers economic factors such as time for transfer, finances or resources needed. Further, transferability exposes the preconditions for transfer such as willingness to adopt by receiving site, reparability or documentation completeness (E. B. Grant & Gregory, 1997, p. 998). Hence, a screening for an adequate location, which meets the requirements from the previous step, should determine the relevant plant(s) within an IMN. Afterwards a concrete technology concept is derived. A detailed concept and implementation plan is the result of this stage. In a next step, existing processes are adjusted, and the selected technology is implemented. Although not directly mentioned by the case companies, the last steps are knowledge development, performance enhancement and continuous improvement (Thomas et al., 2008). As opposed to the first steps, the last two steps typically belong to the area of responsibility of the receiving site.

Obviously, the level and success of a transfer of technologies depends on economic, social, cultural, and legal conditions in the host and receiving regions (Prasad & Babbar, 2000, p. 223). For example, the technology transfer between industrialized countries tends to be easier due to the existing infrastructure and better qualified employees. Similarly, "cultural compatibilities" enhance technology transfers across locations (Keller & Chinta, 1990, p. 40). A low heterogeneity in terms of culture, location or processes facilitates a transfer (Deflorin et al., 2012, p. 520). In addition, other researchers figured out that know-how typically flows from high-wage or developed plants to less developed locations (Gupta & Govindarajan, 2000; Mudambi, 2008; Szász et al., 2016) or between sites in high-wage locations (Ambos, Ambos, & Schlegelmilch, 2006).

Furthermore, ASC, BEC and CAC are the only companies where *lead* factories receive a remuneration for their supporting activities either directly from the receiving plants or indirectly from the headquarter. The other case companies do not financially support *lead* factories in their tasks, but consider this fact by more conservative growth and development plans.

Proposition H: Digital technologies are extending the range of responsibilities of plants and their roles. Lead factories function as knowledge hubs for developing, operating and distributing such technologies to other locations.

Other site roles such as *contributor*, *server*, *offshore*, and *source* are also found in the case companies' manufacturing networks. Only *outpost* factories were neither identified nor operated by any case company. As all factories must produce goods in some way, *outpost* plants usually have a secondary strategic role (Ferdows, 1997b, p. 76) and are therefore not clearly identifiable. However, independent players (i.e. HAC) and dominant headquarters (i.e. CAC) do not fit any of the plant role classifications. These have the highest autonomy and are responsible for selected technologies regardless of *lead* factories. For example, CAC's headquarter provides IT systems without any interactions or agreement from the *lead* sites.

Besides, *lead*, *offshore* and *source* sites can make use of digital technologies these days. Automation (e.g. automated guided vehicles, smart robotics) and human-machine interfaces (e.g. mobile devices, AR), create productivity gains for these sites and have the potential to lower manufacturing costs. Further, MES, cloud and partially AM are implemented to better address the strategic site roles of *offshore* and *source* factories. Hitherto, *contributor* and *server* sites profit primarily from data analytics and ICT technologies in terms of utilizing internal and external data. In the future, AM is supposed to unlock new potentials for customized production (i.e. MTC). Once again, referring to Ferdows (1997b), the roles and responsibilities of plants can change over time because of three different factors. First, the plant can choose a new role itself. Second, the headquarter can assign a new role or, third, local market forces determine a new role (Hood & Taggart, 1999, p. 515). The latter can be seen in different case studies. A new finding is that sites do not only follow Ferdows' (1997b) evolutionary path, but also change their primary strategic site reasons due to local market forces. For example, some Chinese plants are developing from low-cost sites to *server* respectively *contributor* plants (e.g. at MTC or ASC), which is also partly discussed by Kinkel et al. (2014). An extended plant evolution map can be found in appendix L. By upgrading a plant role, the contribution to the overall IMN increases (Tseng & Chen, 2014, p. 374) and the likelihood of plant closure is reduced (Mediavilla et al., 2014, p. 82). Moreover, it typically enhances both the performance of the individual plant as well as the performance of an IMN as a whole (Nohria & Ghoshal, 1994, p. 499). For instance, as ASC's *lead* factories are responsible for certain products, the development or conception of a new product can result in new *lead* sites in the IMN. On the other hand, the phase-out of a product category can diminish the competences of such a factory.

In summary, digital technologies have the potential to change plant roles in an abstract or physical way. The former is achieved by allocating or extending the areas of responsibility to different sites. For instance, AR or AM change the way *lead* factories operate and support other plants in the IMN. Hence, R&D, production, innovation, and support competences are influenced. Typically, these activities become more advanced (see chapter 6). Furthermore, the manufacturing network changes physically. CAC, EEC and MTC have built new factories and extended their manufacturing footprint. Although digital technologies were not the drivers for these decisions, they are key enablers for supporting efficient and productive manufacturing. Even if products are not reallocated due to the use of digital and automation technologies, these technologies determine the allocation of plants (e.g. EEC's front-end factories). Consequently, plant roles are adapted to respond to the new conditions.

Proposition I: All kinds of plant roles are influenced by digital technologies in different ways and to a different extend. Their strategic site reasons are largely addressed by human-machine interfaces, AM, automation, data, and IT technologies.

6 Implications for high-wage locations & management of IMNs

The aim of this research is an examination of the impact of digital technologies on IMNs and high-wage locations. This chapter will further explain the outcomes of the theoretical, conceptual and empirical stage. Additional recommendations, frameworks and a model are derived to support manufacturing companies in managing their digital technologies as well as high-wage plants in IMNs.

Selected excerpts have been published in the subsequent outlets:

- *Benninghaus, C., & Budde, L. (2018). Digitale Technologien standortübergreifend nutzen – Schubkraft für kollektives Wissen. Industrieanzeiger, 140(7), 28-29.*
- *Benninghaus, C., Budde, L., Friedli, T., & Hänggi, R. (2018), Implementation drivers for the digital industrial enterprise, in: International Journal of Production Economics, In review.*
- *Benninghaus, C., Elbe, C., Budde, L., & Friedli, T. (2018). Digital Technologies – Evolution of production in high-wage countries. Final report. Institute of Technology Management at the University of St.Gallen, St. Gallen.*

6.1 Consequences for high-wage locations

The ability to exploit (new) technologies, innovate processes and products are key enablers for the competitiveness and welfare of high-wage countries (Pavitt, 1990, p. 17). Hence, digitalization and related technologies are a long-term investment to safeguard the existence of manufacturing locations in these regions (Schönsleben et al., 2017, p. 183). From the empirical analysis and literature review, it becomes obvious that several location-specific factors are determining the success of implementation. Further, locations in high-wage areas need to position themselves clearly in an IMN. Nevertheless, digital technologies do not guarantee success, but the clever use of the right technologies ultimately makes it possible to ensure long-term benefits. The holistic integration and socialization task that digital technologies entail must be understood and mastered.

6.1.1 Technological leadership

High-wage locations have further potentials in terms of R&D, production and specific knowledge creation regarding processes, products and technologies. Typically, the degree of innovation (e.g. Global Innovation Index) is higher in developed countries (Porter & Stern, 2001). Therefore, operation managers in high-wage countries need to decide whether they want to seek technological leadership or strive for a follower strategy regarding digital technologies (Matt et al., 2015, p. 340). In the prior case, a location seeks to be the first to introduce technological changes, whereas in the second case it chooses to adopt existing solutions. Leadership is advisable when a firm can exploit several first-mover benefits that unlock competitive advantage. While literature identifies these benefits on business level (Kerin, Varadarajan, & Peterson, 1992; Lieberman & Montgomery, 1988; Porter, 1985b) and in comparison to external competitors, the subsequent first-mover advantages are adapted for plant roles and internal competition between manufacturing sites in IMNs:

- *Pre-empting a position*: A first-mover can introduce a new process or product before other sites do. In this course, it defines new processes and methods and can take responsibility for global training, support, troubleshooting, continuous improvement, or best practice as well as knowledge sharing. Hence, it paves the way for becoming a *lead* factory.
- *Learning curve*: A first-mover has an advantage concerning the learning curve. Its efficiency or know-how will increase.
- *Early profits*: If there are no substitution products, a first-mover can sell its products produced by digital technologies at high prices (e.g. AM). As the factory can serve customers first, customer loyalty will most likely increase. At least temporarily high profits are also possible.
- *Reputation*: A first-mover has a high reputation (e.g. leader or pioneer) regarding its technological skills. Customers or other sites recognize the unique position. For example, CAC's, EEC's and MTC's new plants seek to position themselves as leading providers to show their innovation competences.
- *Definition of standards*: A first-mover can set standards for a technology. Other sites in an IMN have to adopt these standards. Besides, first-movers can apply for a patent, secure copyrights and related protection measures.

However, being a technological leader can also have several disadvantages. Especially costs as well as the uncertainty of the market have contra-productive effects (Kerin et al., 1992; Lieberman & Montgomery, 1988; Porter, 1985b):

- *Pioneering costs*: A first-mover is confronted with high pioneering costs, such as investments in R&D, costs for administration (e.g. regulatory approvals), set up of infrastructure, establishment of service solutions, educating employees, or high material cost due to a small order quantity. Such costs can overcome the first-mover advantages and are mainly responsible for a follower strategy.
- *Shifts in technology or factor costs*: If early investments in the development of a technology are very specific and not transferable to upcoming product or process generations (e.g. transition from mechanical cutting to laser cutting), a first-mover has high factor costs and has to re-invest in its processes. A technological discontinuity favors the followership strategy. Nevertheless, a first-mover can often transfer its experience and learnings also to a new technology.

- *Demand uncertainty*: A first-mover does not have any insights or information about market acceptance or customer's buying behavior. Thus, a technological leader cannot plan its production capacity and investments in advance.
- *Low-imitation costs and "free-rider effects"*: The cost for imitating a technology is often lower than the costs for innovating. In worst case, followers might "free-ride" on the investments once made by the leader by taking over certain technologies (imitation) or taking advantage of weak points of first-mover's solution (entrepreneurial judo) (Lucia Merz, 2016, p. 89).

Each site has to ponder whether the arguments for technological leadership prevail or a follower strategy is more suitable. However, the tendency for high-wage locations should clearly be based on the findings from the empirical studies. Manufacturing will only stay in high-wage countries as long as local markets are relevant or foreign countries have limited capabilities and know-how to push R&D, technological developments and innovation. The following figure 23 outlines this proposition. According to Hofmann & Ruesch (2017, p. 33) who suggest supporting manufacturing companies in their digitalization attempts by providing practical guidelines, the framework shows the possible development directions of sites – regardless of their role, but with reference to their location.

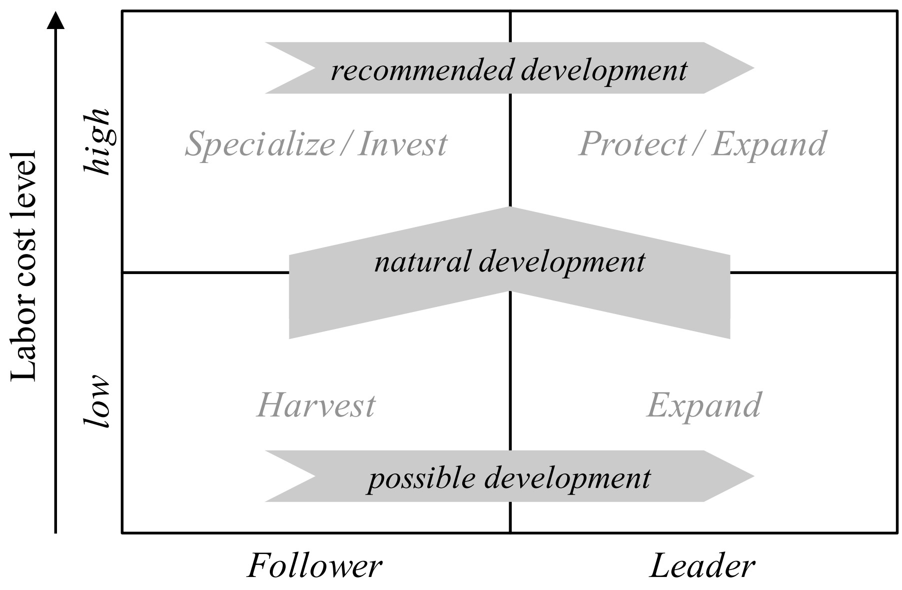


Figure 23: Global technological leader and follower (own illustration)

Following the archetypes, plants in high-wage locations must either specialize or invest to become technological leaders. Leaders in high-wage locations should protect their knowledge and expand it to stay competitive in the future. If leadership is not intended, a plant in a high-wage location needs to look for a niche, which allows a self-sufficient or relatively independent existence as well as operations with less (cost) pressure from other sites. Factories in lower-wage locations not necessarily need to move from follower to leadership. They can either consume from the network (harvest) or provide solutions to the network. If they are already leaders, they should further establish or develop their position. Besides, wages are naturally developing over time (Tate et al., 2014, p. 383).

Consequently, sites in Western Europe have the unique opportunity to extend their competences and knowledge in terms of processes, products and technologies to become or hold the position as technological leaders within their IMNs. If there is more than one factory in a high-wage location, each should look for a specific niche or tasks and dissociate from other plant activities. Hence, factories in high-wage locations are predestined or qualified for taking over the role of a *lead* plant, due to their development path and history (cf. path-dependency). From the empirical study it becomes clear that *lead* sites have capacities and competences for innovating digital technologies and processes as well as introducing new products, which is comparable to the findings of Mediavilla et al. (2014, p. 94). The existing *lead* factories are a good basis, but not a fixed condition as some *lead* sites have only temporary character and might change due to developments in other areas.

Having a look at the future of high-wage manufacturing, plants in high-wage locations need to occupy the position of a technological leader in all six case companies. In fact, knowledge must be preserved and extended in high-wage countries as other nations are increasingly developing. Further, digital technologies can "protect" established locations in Western Europe by making them (even more) efficient. But not only competences in the context of digitalization are strengthening the position of high-wage plants. Other capabilities such as lean management, service or IT pioneering can secure manufacturing activities in high-wage countries as additional responsibilities limit the focus on pure labor costs. This is consistent with the findings of De Treville, Cattani, & Saarinen (2017, p. 80) who argue that these days companies in high-wage locations need to increase sales and margins through innovation, product customization or servitization.

Even if other locations profit equally from the technological advantages after rolling-out digital technologies, high-wage locations need to continuously focus on leadership and being one-step ahead to reduce internal (within IMNs) and external (competitors') competition. Thus, plants in high-wage regions should create, develop, preserve, and renew their knowledge and competences continuously. If required, a knowledge hub function is formed, and codified knowledge is distributed to other plants via different mechanisms (e.g. training, manuals, workshops, projects, job rotation). However, some tactic knowledge cannot be communicated or simply transferred, which gives the site a unique advantage. A similar finding is presented by Vereecke et al. (2006, p. 1748) as plants with a higher level of competence and hence a deeper embeddedness in an IMN are typically more secure and stable. A plant closure becomes less likely (Mediavilla et al., 2014, p. 82). Although such a competitive advantage may have impermanent character (von Krogh et al., 2018, p. 54), a continuous recombination of resources and knowledge (cf. RBV and DCV) allows a sustained competitive advantage through technological leadership. A possible radiation effect on foreign factories can result in locally higher margins. Thus, a successful transfer of technologies and related knowledge leads to cost efficiency and flexibility gains, which is preferable, at least from an overall network perspective.

In conclusion, high-wage locations should take over technological leadership for innovation, R&D or digitalization activities to stay competitive externally and within the own manufacturing network. As "innovation starts with people" (van Laar, van Deursen, van Dijk, & de Haan, 2017, p. 577), this is a great opportunity for locations with access to qualified workforce. The retention of jobs in high-wage countries can therefore be achieved by further expansion of technological innovation and leadership (Brecher et al., 2011; J. Martin & Mejean, 2014; Spring et al., 2017). Such technical core competences provide a unique opportunity as crucial capabilities are restricted to a few sites that are able to achieve such knowledge and excellence (Gallon, Stillman, & Coates, 1995, p. 22). A premise for continuing manufacturing in high-wage countries is that R&D, innovation and manufacturing are not decoupled. Manufacturing is often the first activity of the value chain, which is offshored as it is accompanied by high operating costs and large investments. In recent years, however, other activities related to manufacturing followed the initial production activities and are now performed abroad. Cheng et al. (2014, p. 167) call this phenomenon a "snowball effect". The decoupling of R&D and manufacturing is a controversially discussed field in scientific literature and plants in high-wage locations should not think that manufacturing activities which have been offshored, are likely to come back within the next years.

6.1.2 Differentiation factors for high-wage locations

Apart from the application of technologies, manufacturing activities in low-wage and high-wage regions are different in two more respects: production profitability and planning efficiency (Brecher et al., 2011, p. 21). Typically, manufacturing sites in low-wage countries increase production profitability by focusing on mass production (economies of scale), while factories in high-wage countries position themselves between mass (economies of scale) and variants production (economies of scope). Regarding planning efficiency, companies in lower-wage areas implement robust value-stream-oriented process chains, whereas plants in high-wage countries invest in sophisticated and cost-intensive systems to optimize processes. This trade-off between production profitability and planning efficiency is known as the “polylemma of production”. The dissolution of the opposing poles in the mentioned aspects represents a key element for staying successful in high-wage countries (Brecher et al., 2011, p. 21) and can be addressed by digital technologies. While most entry, standard and large quantity products have been offshored to lower-cost regions, factories in high-wage countries tend to concentrate on high-end, customized and complex goods. Especially, if the customers are located in Western Europe, it becomes most likely that such products are manufactured in high-wage locations. Less developed countries are going to continue to focus on mass production and manufacturing of labor-intensive goods (Eloranta et al., 2014, p. 274). In the future, fewer standard products will be manufactured in Western Europe unless they are produced highly automated or labor cost share is insignificant. Moreover, strategic important components will be produced in high-wage areas to avoid knowledge diffusion. Therefore, the goal must be to produce (multi-variant) products in small quantities or large volumes automatically and economically at high-wage locations. There are no new locations created or manufacturing jobs relocated to Germany or Switzerland due to digitalization, but digital technologies justify, protect and allow efficient production in high-wage locations. Similarly, Szász et al. (2016, p. 771) report that manufacturing plants in more developed areas achieve a higher level of effectiveness improvements in form of quality, flexibility and delivery compared to other sites. Thus, digitalization has a supportive and enabling character.

Based on their long-term experiences, sites in high-wage countries could also derive new business models, service offerings or products to generate additional income sources. For example, HAC’s high-wage locations have large development capacities. In combination with qualified employees, this is a chance for plants to take over responsibility to develop worldwide solutions. Thus, plants in high-wage locations could adopt a leading position also from a product perspective. As product quality levels approximate worldwide, focusing on quality alone will not be a lasting or unique selling point for plants in high-wage locations in the future. This finding qualifies the statement by Martin & Mejean (2014), who assume that increasing quality levels lower competition. Instead, innovation and flexibility are becoming increasingly important differentiation factors. Nonetheless, quality levels need to stay at a high level in high-wage factories due to the fact that quality is typically a fundamental prerequisite to sell products.

6.1.3 Location-specific factors for operating digital technologies

When managing digital technologies, each company must answer questions about what, where (location) and when (timing) a technology should be implemented as "integrating and exploiting new digital technologies is one of the biggest challenges that companies currently face" (Hess et al., 2016, p. 123). To answer these questions, a company must review its strategic objectives. The choice of location is dependent on various factors. The following digital-manufacturing-location model (figure 24) recapitulates and summarizes the findings of this research regarding relevant location factors for implementing and exploiting benefits of digital technologies. It demonstrates explicit criteria, which determine the adequacy of a certain location. Apart from the outcomes from the cross-case analysis, the model is augmented with aspects of Porter's (1985a) "value chain" concept and the "St. Galler management model" (Rüegg-Stürm, 2005). The findings from literature review (table 4) supplement these categories. A slightly different, rough draft was published by Benninghaus & Budde (2018, p. 29).

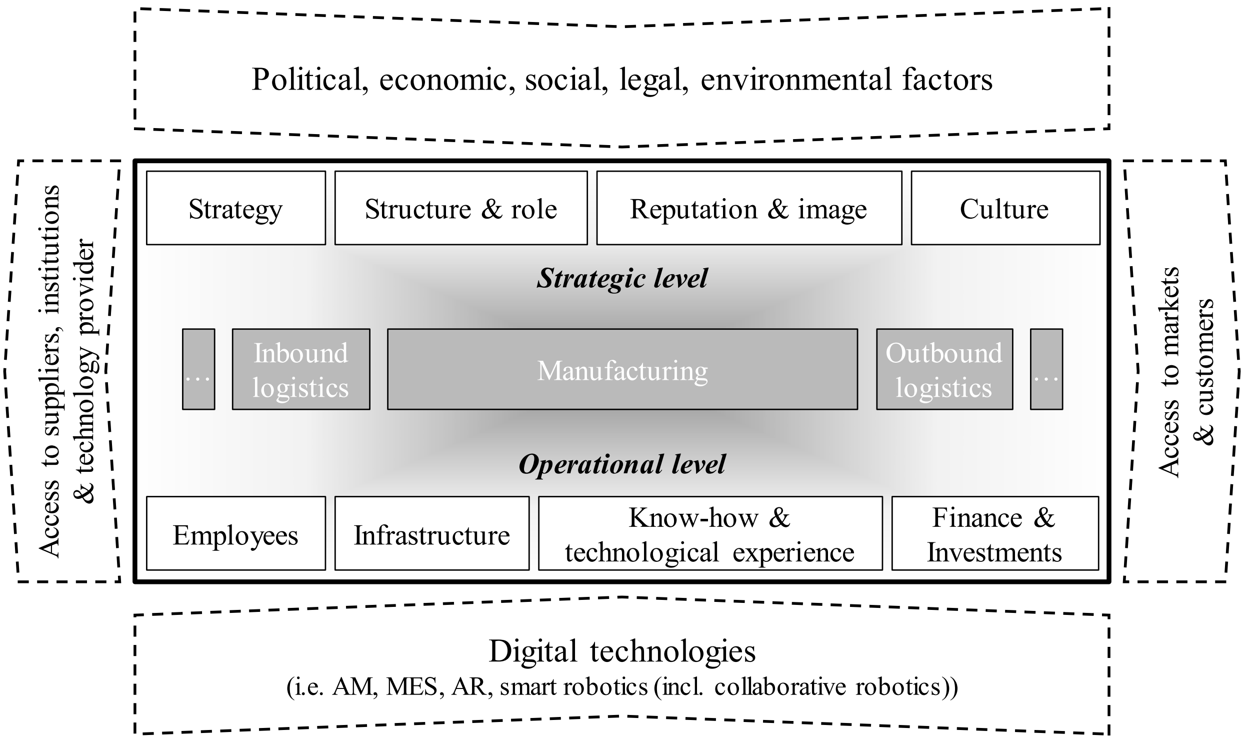


Figure 24: Digital-manufacturing-location model (own illustration)

The model is modular and limited to a few main variables to reduce overall complexity (Porter, 1991, p. 106). Especially, external location-specific factors such as political, economic, social, legal, or environmental characteristics are not further detailed (cf. upper broken box). In this context, examples of political or economic factors are subsidies or industrial policies to facilitate growth and improve business environment. Each location offers a wide range of external location factors, which influence the successful execution of manufacturing tasks. Besides the external location-specific factors, proximity to other stakeholders in a value chain is important (cf. broken boxes). Suppliers, institutions (e.g. universities and research institutions), technology providers, and customers are crucial partners for developing and operating digital technologies (chapter 5.4) – either for collaboration or to facilitate low logistics costs. Such proximities improve innovation and delivery reliability as well as typically increase variants, as customized products are offered to enhance customer loyalty (Kristianto et al., 2017, p. 611). These "business ecosystems" (Gawer & Cusumano, 2014, p. 418) facilitate a location decision as their existence is limited to some regions. In the cross-case analysis it was identified that, at least presently, such business ecosystems are more recognized and considered to be value-adding in high-wage regions in Western Europe or selected Asian countries. Ferdows et al. (2016, p. 64) confirm that such ecosystems are more sophisticated in high-wage regions.

The inner box, which represents a manufacturing factory, differentiates between primary activities (grey area) and the strategic as well as the operational level. Each plant maintains several processes or primary activities such as manufacturing, inbound or outbound logistics, etc. (Porter, 1985a). As this research concentrates on manufacturing, other possible activities are neglected. At the strategic level, companies have to consider their local strategy as well as the structure and role of each site. The case studies make obvious that even now plant roles are indirectly determining the use of digital technologies. For instance, more advanced *lead* or *contributor* sites are implementing high-end technologies to accelerate and ease hardware and data automation. Facilities with fewer competences or dissimilar roles use other technologies or have different reasons for implementing these technologies. Reputation and local culture are also important characteristics. Only if these factors indicate that an implementation of a new digital technology will be beneficial and accepted by the employees, a company should choose the respective plant. Furthermore, operational factors such as employees, infrastructure, know-how, technological experience, as well as finance and investments of each site must be reviewed. For example, depending on the specific digital technology a minimum infrastructure in terms of internet speed or electricity is essential and therefore often an exclusion criterion for setting up a facility. Likewise, technological experience, capabilities (e.g. lean management and working processes) and local financial budget are necessary to implement and maintain a technology. Detailed arguments have been discussed in chapter 5.4. Although the application of digital technologies could be imitated by other sites or competitors, the related skills and experiences are an asset for a high-wage location. Besides, employees are even more important. The empirical studies have shown that mainly qualified employees are required for implementing and operating digital technologies. Typically, complex products are manufactured and high-performance machines are implemented in high-wage regions as the required employee qualification tends to be higher. In their literature review Van Laar et al. (2017, p. 583) identified so-called 21st-century digital core skills: technical, creativity, communication, information management, collaboration, critical thinking, as well as problem solving skills. Moreover, contextual skills have been derived (self-direction, flexibility, ethical and cultural awareness, lifelong learning), which are necessary to fully exploit the benefits of the core skills. These proficiencies of qualified employees are shaping a company's competitiveness and innovation capabilities (van Laar et al., 2017, p. 582). Schools and universities in high-wage areas should foster the imparting of these skills. Frey & Osborne (2017, p. 261) are convinced that "as robot costs decline and technological capabilities expand, robots can thus be expected to gradually substitute for labor". While the number of direct blue-collar workers is declining, some case companies report increases in white-collar employee numbers (e.g. engineers, computer scientists). Whereas the need for qualified employees with sophisticated IT competences is rising (Huber, 2016), the threat of increasing unemployment due to digitalization is omnipresent from a political and social perspective. The application of digital technologies or "computerization" in general will most likely eliminate many manual and routine jobs, which has been a normal process over the past decades (Frey & Osborne, 2017, p. 255). But even non-routine jobs in design, marketing, transportation, or R&D might be substituted (Brynjolfsson & McAfee, 2014; Frey & Osborne, 2017). An example is the increasing replacement of fork-lift drivers by autonomous transport systems. A comprehensive overview has been derived by Frey & Osborne (2017). Although, at worst, some jobs will be eliminated due to the use of digital technologies, it is important to understand that this strategy of automation will secure other jobs in high-wage countries. Hence, digital technologies have a job retention effect and consequently the overall employment is not going to significantly change in high-wage areas in the next years. From a low-cost production perspective only a few regions are promising, as they also offer qualified employees and infrastructure. Even though the education and knowledge levels are rising in China, there is still a shortage of qualified employees as many companies are competing on the factor market. Due to the progressive implementation of digital and high-performance technologies, which require even more qualified or semi-skilled operators, "high-quality labor has been exhausted" in China (Tate et al., 2014, p. 384).

Based on the case sample, it can be concluded that depending on the company, their high-wage locations address most factors of the digital-manufacturing-location model (figure 24) satisfactorily or even exceed the requirements. Thus, another consequence for high-wage locations is the continuous improvement and adaptation of their strategic and operational level to fulfil the minimum requirements to implement digital technologies. In fact, this approach can improve their competitive position. Even high-wage locations still have additional improvement potentials concerning internal efficiency and productivity. This applies in particular to highly innovative companies that are regularly introducing new products or production processes. These attempts are often not yet optimized and still hold "perceptible efficiency potentials" resulting from process improvements (Kinkel & Maloca, 2009, p. 161). For example, managers at HAC are aware that their high-wage sites still offer potentials in terms of lean management, material flow or waste reduction. This could be reinforced by a realigned production system as well as the use of digital technologies in form of automation and data solutions.

Finally, a clear consequence for high-wage locations can be the expansion of capacities and establishment of new sites (cf. CAC, EEC, MTC). These sites are typically largely equipped with digital technologies and comprise most aspects of the digital-manufacturing-location model (figure 24). Additionally, they profit from subsidies and tax benefits. Apart from high productivity in manufacturing operations and innovation processes, the new digitally enhanced sites function as forerunners in their IMNs and are seen as marketing tools to attract customers and potential employees. The high reputation of the label "made in Germany (or Switzerland)" further strengthens the position of factories in high-wage counties.

6.2 Consequences for IMNs and network configurations

Digitalization of manufacturing activities will continue in high-wage as well as low-wage locations as technology and automation implementations increase worldwide. For example, the global robot sales grew by 12 percent per year from 2011 to 2016. On average around 309 industrial robots were implemented per 10,000 employees ("robot density") in the German manufacturing industry in 2016 (International Federation of Robotics, 2017). At the same time, robotic prices have declined by 10 percent annually (Frey & Osborne, 2017, p. 261). In this context, conventional automation in form of machining centers is typical for lower-wage locations to increase process and product quality, whereas high-performance automation centers are implemented in high-wage countries to reduce direct labor cost. Although robotics in general are no new technologies, most companies have just started to automate and slowly implement robotics. Smart and collaborative robotics, on the other hand, are relatively novel, even more advanced and still less implemented. To limit offshoring activities or elimination of jobs in higher-wage countries, collaborative robotics are a promising solution, which allows an adequate automation of smaller product quantities. This technology is predominantly implemented in high-wage plants. Despite these facts, it is definitively important that local processes are set up and configured correctly, before implementing a new (digital) technology. Otherwise, the extended use of digital technologies will affect the specific process negatively, by increasing complexity, rework time, machine downtimes, costs for quality, or failures. Hence, an optimized process is a precondition for integrating digital technologies. At this point, an established lean concept can foster process optimization. As "the process of making manufacturing more efficient has to be efficient itself" (Menascé, Krishnamoorthy, & Brodsky, 2015, p. 206), process understanding is a fundamental requirement for integrating and operating digital technologies (Benninghaus, Budde, et al., 2018). In this context, excellent data quality is another prerequisite for the successful implementation of digital technologies. But often the main problem for companies is rarely a technological problem, but a management and organizational issue (Friedli, 2006, p. 18). As a recommendation, a systematic technology screening, evaluation and conformity with the manufacturing strategy should be considered before investing in a new technology, although the evaluation of digital technologies is a time-consuming and challenging project. Each company must estimate for themselves if and to what extend digital technologies are relevant for its operations. An early assessment of the derived plant-technology-competence framework (figure 12) can help to structure this attempt and might prevent redundancies and undesired activities in an IMN.

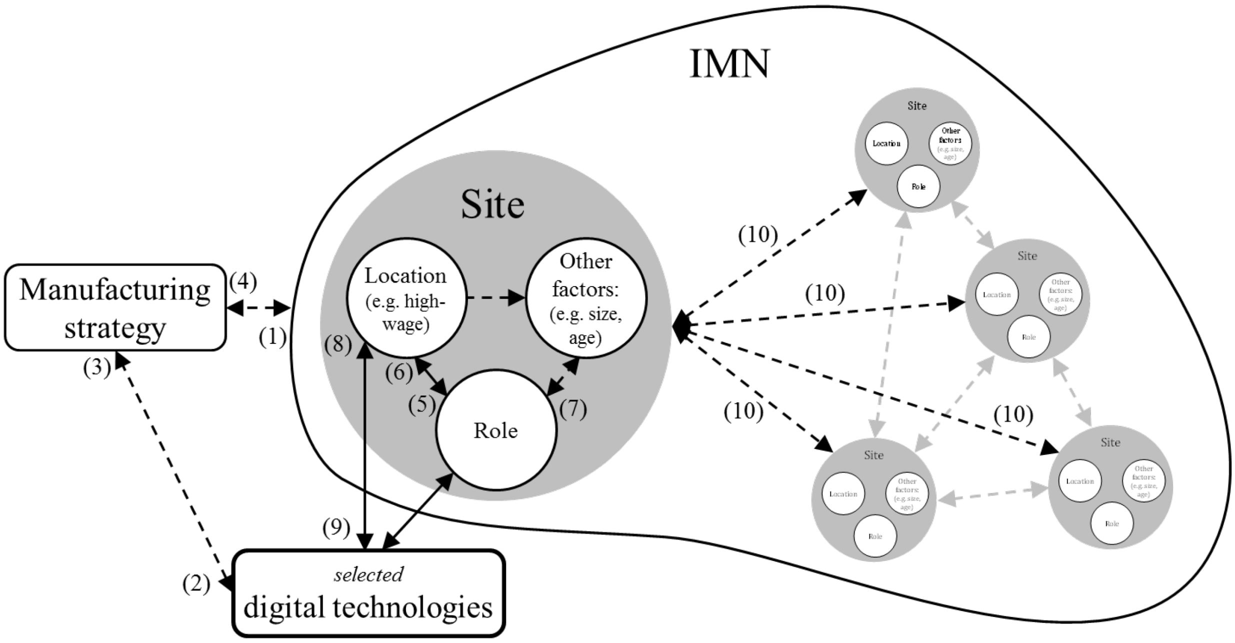
The application of digital technologies varies according to company-, industry- and location-specific factors. While most digital technologies are implemented first or exclusively in plants in high-wage areas, others such as IT systems, RFID, MES, or Big Data analytics are often employed in factories around the globe at the same time. With focus on IMNs, AM, AR, MES and smart robotics (including collaborative robotics) seem most promising for changing plant roles and the configuration and coordination of sites. On the one hand, such technologies can and will be used to automate processes, steer plants, increase quality levels, or reduce direct labor costs. On the other hand, selected technologies such as AR or MES support the coordination of manufacturing operations. Subsequently, competences and tasks of plants (i.e. *lead* factories) are refined or extended either for testing, implementing, operating, or supporting other plants with certain digital technologies. For example, the broad usage of AM will probably change IMNs significantly in the next 10 to 20 years. The empirical studies revealed that decentralized network approaches (cf. EEC and HAC) result in different technological setups and low standardization. Further, many redundancies characterize such IMNs. A retroactive harmonization of plants and network setups is cost-intensive and time-consuming. To avoid such developments, internal transfer centers or *lead* factories could support an efficient knowledge sharing, capability expansion and enforcement of standardization. Thus, *lead* sites with – at best – clearly assigned responsibilities and competences are a promising approach. These natural or strategically defined *lead* factories balance centralization and decentralization advantages. They are able to manufacture high-quality products and are in charge of R&D, training, support, continuous improvement, knowledge sharing, ramp-up, technology development, and testing. Most of these aspects will become even more pertinent under the umbrella of various digital technologies.

Depending on the specific product type and volume, total or landed cost calculations offer detailed facts about actual costs for manufacturing a specific product in a selected site. In this context, it is important to consider the wages of low-skilled and qualified employees. For instance, manufacturing operations in Eastern Europe are increasing in importance. Although labor costs are higher compared to China, logistics and coordination costs are lower from a Western European point of view. Moreover, steering and supporting these plants is simpler due to geographical and cultural proximity. When considering replacing blue-collar workers by automation solutions, a company should reflect the costs for employing a specialist to operate the technology. The savings can be marginal, if the retrenchments from eliminating blue-collar jobs are limited. The example of MTC shows that an aggregation of transportation, procurement and manufacturing costs results in almost no cost advantage in Asia compared to Europe.

In conclusion, even if the network configuration is not always physically changed, digital technologies have the potential to redefine tasks and roles within an IMN. Further, digital technologies may reduce the price gap between regions by improving production efficiency of both direct and indirect activities. Consequently, the advantages of low-cost areas cannot be exploited when high automation or technology utilization is affordable and achievable. However, technological and production capabilities have increased in lower-cost countries in recent years. Nowadays, many manufacturing sites in low-cost countries are on a similar performance level compared to plants in high-wage regions. For the next few years there is still a competitive advantage in Western Europe in terms of process and technological know-how, but this might change within the next 10 to 20 years. As a result, the primary strategic sites reasons will alter over time.

6.3 Revised research framework

In the following, the research framework presented in chapter 1.5.2 will be updated and refined based on the findings from literature, the conceptual part and the empirical cross-industry studies (see figure 25). The coherencies and dependencies will be explained below.



(1, 2) (Fine & Hax, 1985; Hayes et al., 2005; Hill, 2000; Miltenburg, 2005; Skinner, 1996; Slack & Lewis, 2002); (3) (Yoo et al., 2010); (4) (Miltenburg, 2009); (5) (Szwejczewski et al., 2016); (6) (Ketokivi et al., 2017); (7) (Demeter & Szász, 2016); (8) (Abele et al., 2008); (9) (Ferdows, 1997b); (10) (Cheng et al., 2011; De Toni & Parussini, 2010; Feldmann et al., 2013)

Figure 25: Revised research framework (own illustration)

A manufacturing strategy comprises structural and infrastructural levers. On the one hand, these dimensions directly affect plants, roles and the use of (digital) technologies (1, 2). On the other hand, digital technologies are an essential part of strategy development (3) and a strategy is subject to specific locations and environmental conditions (4).

Location determines decisions whether a plant is located in a low-cost or high-wage country. As “plant location is one of the key factors that determines its strategic role” (Szwejczewski et al., 2016, p. 125), the choice of location has a significant impact on site roles (5). The case studies confirmed this fact, as they described the tendency for locating *lead* factories in Western Europe and *offshore* or *source* plants with access to low-cost production factors in Eastern Europe or Asia. On the other side, plant roles also influence location decisions (6). These relations highly depend on the perspective. For instance, in the first case an existing location can occupy a new role (location exists before role is defined) or in the second case, it is required to establish a new plant with a distinct role or function to address the overall strategy (role is pre-defined before location is established). Hence, this can lead to a kind of *egg or chicken* causality dilemma. Additionally, other factors such as size, age or capacity influence plant roles (7). Especially, age determines roles as it is typically correlated with technological experiences and histories, which provides a competitive advantage for a facility. A similar effect on plant locations (or from roles on other factors) is identified neither in literature nor in the empirical studies. These missing connections were not further investigated since they are beyond the scope of this research.

Digital technologies affect locations (8). As described in the empirical part of this thesis, some technologies are more utilized in high-wage regions than others. Further, objectives for implementing digital technologies vary across locations (e.g. automation to increase quality in low-wage regions or to lower direct labor costs in high-wage countries). However, technology influences location decisions and vice versa. In fact, not all locations have access to specific technologies (9). Typically remote or low-cost regions cannot apply high-end technologies due to missing know-how, competences and provider support. This is consistent with Ferdows (1997b), who described this fact for conventional technologies. Moreover, technology utilization is a result of plant roles. *Lead*, *contributor*, *source*, or other factory types use different kinds of technologies to address their primary strategic site reasons. Specifically, *lead* factories have broad responsibilities regarding digital technologies because they develop, implement, operate, and transfer such systems. At the same time, the degree of automation and type of technology employed determine plant roles. Specific technologies, experiences, competences, and know-how inevitably result in either explicit or implicit site roles. Again, depending on the point of view, it is an *egg or chicken* dilemma.

If we look at coherencies and dependencies from the wider IMN perspective, both the cases and literature confirm that factories affect other sites in an IMN (10). An upgrade of a plant role or changing responsibilities of a factory inevitably have an impact on other sites.

Finally, the revised research framework complements the research at hand by presenting and explaining the main dimensions and elements of plants, digital technologies and IMNs. It provides a comprehensive overview of the main coherencies and contributes to a better understanding and integration of two topics that have been separated in previous scientific and practical discussions.

7 Conclusion and outlook

The last chapter will complete the research project. It will summarize the research outcomes and provide a critical reflection with reference to the initial RQs (7.1). Afterwards, the distinct contributions to theory and practice are presented in subsection 7.2. Finally, underlying limitations of this research as well as suggestions and ideas for future research are discussed (7.3).

7.1 Summary of results and critical reflection

After the presentation of the practical relevance and scientific interest of this research, it became clear that plants in high-wage locations are under increasing pressure based on external and internal competition. In connection with the emerging field of digitalization respectively digital technologies, these locations might benefit from a more advanced technological setup to unlock new competitive advantages. Hence, several gaps that address theoretical deficiencies and practical issues were derived and formulated in a main RQ:

Main RQ: What is the impact of selected technologies on plant roles in high-wage locations in the context of international manufacturing networks?

In order to answer and structure the main RQ, the following sub-RQ have been derived. In the following, each sub-RQ will be revisited and discussed based on the theoretical, conceptual and empirical findings of the underlying research.

Sub-RQ1: What digital technologies have the potential to impact plant roles in international manufacturing networks?

The impact and benefits of digital technologies are among the most discussed topics in the context of digitalization in academia and practice. Many case companies have already implemented multiple digital technologies as most companies do "not start their digital transformation journey from zero" (Berman, 2012, p. 18). This research has identified 30 technologies in the context of digitalization and discussed their relevance with industry experts. These technologies were classified into (1) automation and manufacturing technology, (2) data analytics and ICT, (3) human-machine interfaces, and (4) embedded systems. Further, the technologies have been filtered according to Wheelwright & Clark's (1992) funnel model. Based on the input from the "Swiss Manufacturing Survey", TRL and attributes of digital technologies, the 30 technologies have been ranked and sorted. In this context, smart robotics (including collaborative robotics), automated guided vehicles and augmented reality were pre-selected for the subsequent discussions. However, during the six cross-industry case studies, automated guided vehicle technologies were excluded from the list as they apparently had no effect across plants. Even if MES and AM are no digital technologies by definition, they were added to the list, as their potential impact on IMNs is high. Additionally, other data-based technologies have been briefly discussed.

To combine the topics digitalization and IMN configuration, the *lead* factory concept of Ferdows (1997b) has been chosen after careful evaluation of different criteria. In fact, this typology is the one most appreciated by the scientific community, the one empirically tested and the one most valid due to its focus on manufacturing companies as well as its affinity to industrial practice. It should be noticed, however, that site roles are theoretical constructs to describe tasks and responsibilities of manufacturing plants. As seen in practice, manufacturing sites cannot easily be assigned to one approach and may take over roles from multiple role typologies at the same time.

Notwithstanding, the impact of digital technologies on plant roles can be discussed from a general and a specific point of view. In general, digital technologies have the potential to reinforce existing site roles and extend the level of competences of factories. For example, on the one hand, *lead* sites receive more development competences, and, on the other hand, digital technologies exploit the successful execution of activities and processes locally. Thus, digital technologies indeed do extend tasks and responsibilities of plant roles. Especially *lead* plants are knowledge hubs and assume responsibilities for developing, implementing, operating, and transferring digital technologies. Digital technologies also address the specific strategic site reasons and therefore are central elements to strengthen their positions in IMNs. Again, *lead* factories balance centralization and decentralization advantages and have responsibilities, among others, for R&D, training, support, knowledge sharing, and ramp-up. Although the primary strategic site reason *access to skills and knowledge* is not directly addressed by digital technologies, the access to qualified employees and know-how is crucial to develop and implement digital technologies. In fact, access to qualified employees and know-how are the most critical factors for manufacturing companies in the context of digitalization. Other factors such as supplier access, infrastructure, technological experience, investments, reputation, or culture foster an efficient implementation (cf. digital-manufacturing-location model).

The primary strategic reason of *offshore* and *source* sites is *access to low-cost production*. Through automation (e.g. automated guided vehicles, smart robotics) and human-machine interfaces (e.g. mobile devices, AR), these site can exploit productivity gains and have the potential to lower manufacturing costs. Savings can be especially significant for mass production goods. Furthermore, ERP, MES and cloud computing are implemented to better exploit the primary strategic reasons of *offshore* and *source* factories in form of data collection and provision. However, in contrast to the other primary strategic reasons defined by Ferdows (1997b), access to low-cost production will become less important in the digital age. While access to skills and qualified labor typically exists in Western Europe, access to low-cost production factors is mostly realized in Eastern Europe. China's initial advantage of low labor cost is being substituted by access to markets and customers. *Contributor* and *server* sites are primarily concentrating on *proximity to markets* and customers. They profit from data analytics and ICT technologies such as ERP, MES and cloud computing by utilizing internal and external data. AR solutions are partially implemented to support manufacturing, sales and marketing activities. In the future, AM and AI are supposed to unlock new potentials for customized production. *Outpost* is the only plant role in Ferdows' (1997b) typology that has not been identified in the case studies.

Altogether, automation, human-machine interfaces, data analytics, and ICT technologies have the highest impact on plant roles as well as high-wage locations in IMN. From the conceptual and empirical part of this research, it becomes obvious that these technology classes and related specific, digital technologies have the potential to alter responsibilities and reinforce plant roles. Only technologies belonging to the class of embedded systems have marginal influence as they are typically no standalone solutions. Although most digital technologies have or are expected to have a high impact on plant and network level, many challenges and barriers which are limiting the successful execution of digital technologies are still unsolved. Challenges regarding digitalization occur in different dimensions such as technological, political, social, economic, or legal (Magruk, 2016).

Sub-RQ2: How could the implementation of such technologies change the configuration in the context of international manufacturing networks?

From an IMN perspective, network configuration can be transformed in two ways due to the implementation of digital technologies. On the one hand, IMN configuration can be changed physically by closing or establishing new sites. Although digital technologies are not the drivers for this decision, they are key enablers for supporting an efficient and productive manufacturing. In fact, three out of six case companies recently built new facilities in high-wage countries that serve as *lead* factories. Therefore, the utilization of digital technologies can result in new plants, as digital technologies are supposed to improve internal efficiency and productivity. Apart from productivity gains in manufacturing operations, the new digitally enhanced sites function as innovation, marketing and manufacturing forerunners within their IMNs.

On the other hand, network configuration is altered immaterially due to site specialization in form of new product, task and responsibility reallocations. For example, entry, standard and large quantity products have been offshored to low-wage regions. Plants in high-wage countries tend to focus on high-end, customized and complex goods. While some companies (e.g. CAC) report product reallocations that are related to increases in quality due to robotics, EEC allocates whole factories based on digital technologies (cf. front-end factories in Europe). Consequently, plant roles are adapted to respond to dynamic conditions. In particular, AM, AR, MES, smart and collaborative robotics seem most promising for changing network configuration. For instance, AR or AM change the way *lead* factories operate and support other plants in an IMN. As a result, competences and tasks of plants are adapted, refined or extended. Thus, AM and robotics do not only initiate new development, production, innovation, and support competences of *lead* plants, they are also drivers for product reallocations. These digital technologies can and will be used to automate processes, boost quality levels, or reduce direct labor costs. Moreover, AR and MES are technologies, which directly influence and improve coordination aspects within an IMN. For instance, all six case companies use MES to steer and coordinate manufacturing network operations. Such technologies have the potential to reduce transaction costs for communication, collecting information and controlling. Although this research focuses on the configuration perspective of IMNs, several coordinating aspects have been discussed in the previous chapters. This confirms Rudberg & Olhager's (2003, p. 36) assumption that network coordination is dependent on configuration decisions. As another example, some *lead* factories have responsibility regarding troubleshooting, training, knowledge exchange, or support, which is enhanced and simplified by AR. Thus, digital technologies have a supportive and enabling character in the context of IMN configuration.

It becomes clear that digital technologies are not drivers, but enablers for efficient manufacturing operations in high-wage countries. But most changes in network configuration are not purely based on digital technologies. It is difficult to determine what developments are exclusively enforced by digital technologies and what share is attributable to strategy adaptation, market developments, production system enforcement, or other process improvements (e.g. lean principles). However, as most required location factors (i.e. access to knowledge and qualified employees) for a successful application of digital technologies are available in high-wage locations, supreme consequences might be the establishment of new manufacturing facilities or capacity expansion.

Sub-RQ3: What are the consequences for high-wage locations and the management of international manufacturing networks as a whole?

The ability to develop, apply, and exploit digital technologies can enhance the competitive position of a manufacturing site. From literature and the empirical outcomes, it becomes clear that digitalization of manufacturing is the only way to keep manufacturing activities in high-wage locations. The pressure on margins in high-wage locations leads to pressure for process and product innovations. Even though digital technologies are not the drivers for keeping or extending manufacturing activities in high-wage countries, they function as key enablers. If digital technologies are applied, offshoring activities from high-wage locations to foreign countries are less probable since digital and automation technologies reduce direct labor cost and increase plant efficiency. As these technologies become more affordable and reliable, the only reason for relocating manufacturing activities would be changes in markets or access to new customers. Proximity to markets and customers is still one of the main arguments concerning location decisions. Hence, manufacturing sites will still be primarily located close to markets to serve customer segments local-for-local and timely. However, access to knowledge and qualified employees has a similar relevance. Proximity to qualified employees becomes a critical lever in the context of digitalization and compensates the location factor access to low-cost manufacturing. This is a unique chance for employers in high-wage regions. On the one hand, the education systems in Western Europe allow a purposeful education and training of (future) employees. On the other hand, research and industry clusters offer the opportunity to hire additional experts from different sectors. Whereas less developed countries are going to continue to manufacture mass production and labor-intensive goods, highly complex, multi-variant products are going to be manufactured in high-wage regions. In this context, conventional automation is typical for lower-wage locations to increase product and process quality levels, while high-performance automation systems are implemented in high-wage countries to reduce direct labor costs.

All these aspects allow a compensation of low-cost manufacturing advantages in foreign countries. Consequently, the advantages of low-cost areas cannot be exploited when high automation or technology utilization is affordable and achievable. However, the large number of existing manufacturing sites and new established sites in high-wage regions show that not only cost advantages are important for operating an IMN. Apart from efficiency gains and cost factors, technological and related knowledge leadership as well as innovation capabilities for new products, services or business models are building blocks for staying competitive in high-wage countries. Especially, the advantages of technological leadership are omnipresent. The combination of knowledge, product, process, and technology competence justifies and secures activities of plants in high-wage locations. Hence, manufacturing sites in high-wage locations should take over typical responsibilities assigned to *lead* factories and concentrate on product and process innovation, implementation and testing of (digital) technologies, knowledge creation, product customization, and operational excellence. Further, automation technologies have the potential to reduce direct labor costs. According to the case studies the *lead* factory is the most frequently applied role for plants in high-wage countries. As *lead* factories are regularly located in a high-wage environment, substantial labor cost savings are essential. In addition, the consequences of demographic change in high-wage areas can be also addressed by collaborative robotics and human-machine interfaces such as AR, mobile devices or wearables.

As a result, sites in Western Europe have the unique opportunity to extend their competences and knowledge in terms of processes, products and technologies to obtain or hold the position as technological leaders within their IMNs (figure 23). Even though other plants benefit equally from digital technologies after a technology transfer, *lead* factories and accordingly high-wage locations need to continuously be the forerunners to reduce internal and external competition. In combination with qualified employees, digital technologies are critical enablers for an efficient and innovative production in high-wage regions. Nowadays, they are real job retention measures and make it possible to ensure the adaptability of a location. The consequences for high-wage locations range from redefined plant roles (e.g. new *lead* sites), extended or new responsibilities (including knowledge creation) to the establishment of new factories. Other locations in the IMN are affected by such changes. For example, new factories and new plant roles result in a competence and support realignment in a manufacturing network. Hence, high-wage plants must consider their strategic position. If high-wage sites become unprofitable or lose their innovation and knowledge hub role, activities are likely to be offshored. That confirms that most location decisions are temporary considerations, based on current conditions and affected by uncertainty. As the productivity of foreign sites increases faster than local labor costs, high-wage locations have to occupy a clear position to avoid offshoring decisions.

Nonetheless, a systematic management and network design is a precondition. Companies that do not systematically define plant roles and IMN structures typically have many isolated digitalization projects and activities that are not interlinked and end in isolated applications. The consequential redundancies result in higher costs, double function, waste of resources, and extra work for standardization (e.g. CAC, EEC, HAC). Hence, as derived from the case studies, both the management of IMNs and digitalization activities must be coordinated. In this respect, the plant-technology-competence framework (figure 12) can help to structure such approaches and support decision-making.

7.2 Contributions to theory and practice

7.2.1 Contributions to theory

The research is rooted in the field of international operations management. It refers to Ferdows' (2018) call for more research in operations management and, in particular, research on the impact of new technologies on IMNs. To the best of the authors' knowledge, this research is the first that ties together two subjects, which are usually studied and examined separately. From a scientific perspective, this study contributes to an enhanced understanding regarding the impact of digital technologies on plant roles, manufacturing networks and high-wage locations. In some ways, industrial companies might be ahead compared to academia in the field of digitalization (Ferdows, 2018, p. 399). The refined research framework (figure 25) outlines the primary coherencies and until recently missing links. Hitherto, most researchers used the term technology and digitalization without any specification. Thus, the research extends the knowledge base of digitalization, digital technologies, IMNs, and plant roles. This thesis might be a starting point for further research as both digitalization and IMNs have several connecting factors.

A vital contribution of this research is the further development of a formal definition of the term *digital technology*. The existing definitions by academics and practitioners are broad and not applicable in parts. The author is convinced that the derived definition and related description model (figure 4) are, on the one hand, accurate and detailed enough for most discussions as well as applications. On the other hand, they are extensive enough to represent and reflect additional and upcoming technologies in the context of digitalization. The classification of digital technologies complements the definition and provides a clear structure for digital technologies. In this regard, 30 technologies in the context of digitalization have been identified, their individual TRL level evaluated and sorted according to the derived definition and classification. It became obvious that connectivity, compatibility and interoperability of digital technologies are of the utmost importance and that various technologies cannot be considered in isolation. However, several technological barriers such as missing standards, demanding data management or IT security are still unsolved issues in the context of digital technologies (Hofmann & Ruesch, 2017, p. 24).

The research complements prior studies applying RBV or DCV in the context of IMNs. It was identified that digital technologies can be a source of competitive advantage.

Although single digital technologies can simply be bought or implemented, the knowledge to successfully and efficiently operate and develop these technologies is a crucial competence in terms of internal and external competition. These competences are rare, difficult to replicate and imitate, which is in line with the assumptions of RBV and DCV.

Another contribution to theory is the systematic review of plant roles. In total, more than 60 plant roles have been identified from a literature review (table 5). The main finding is that most roles are based on only a few main typologies from Bartlett & Ghoshal (1986), Ferdows (1989, 1997b) and White & Poynter (1984). After outlining the similarities and differences of these typologies, Ferdows' (1997b) plant role concept has been further examined in the empirical studies. In fact, this role typology has a high affinity to industrial practice and addresses the needs of manufacturing footprints. The findings from the case companies regarding additional responsibilities, technical competences and tasks of Ferdows' (1997b) *lead* role are the first with focus on digitalization. Among others a modification of Ferdows' (1997b) plant evolution map has been derived (figure 27). Hence, this research supplements and extends the scientific discussions on plant roles.

Last, the developed digital-manufacturing-location model (figure 24) presents the relevant location factors for developing, implementing and exploiting digital technologies. The model proposes explicit criteria, which determine the adequacy of a certain location. It is based on the cross-case analysis and combined with the works of other authors. The digital-manufacturing-location model provides transparency and forms an integral system. This overview offers potentials for digital technology allocation, location decisions or can assist a systematic planning of IMNs. It is rather useful for unplanned and unstructured IMNs and can be also considered as a practical contribution to advising plant and IMN managers.

7.2.2 Contributions to practice

Practical issues observed in the field and brought up by managers of manufacturing companies motivated the object of study. Hence, the findings of this project seek to support companies in managing their digital technologies and IMNs more efficiently. The research at hand provides several frameworks, models and recommendations. It overcomes the often purely technical perspective of digital technologies. The strategic approaches provide guidance for operational and plant managers in defining an advantageous setup of their IMNs and high-wage locations. The research introduces manifold plant role typologies, which can motivate and support practitioners to clearly structure their IMNs based on existing typologies. Hitherto, many companies do not systematically discuss or derive plant roles. A clear allocation of resources, responsibilities and competences can help exploit further benefits. Plant managers of high-wage production facilities can profit from a new perspective by not concentrating exclusively on efficient manufacturing activities, but also on possible contributions to the whole network. This practical contribution is vital, since this research might also motivate other companies to re-think the importance of their high-wage manufacturing locations.

The guiding recommendations for positioning plants and technological leadership are an additional contribution to practice. Plants in Western Europe have the chance to extend their competences in the fields of processes, products and technologies to gain or hold the position as technological leaders. Such sites can base their activities on technological experiences and benefit from a positive learning curve, increased reputation, early profits, etc. The specific location factors have been summarized in the digital-manufacturing-location model (figure 24).

Moreover, different technologies in the context of digitalization have been discussed and the impact on the whole manufacturing network analyzed. Although digitalization is actually not a new paradigm and most approaches are a recombination or technological advancement of existing concepts, most companies are not aware of the potential of digital technologies in combination with their manufacturing footprint. For example, smart and collaborative robotics facilitate process automation and replace manual, repetitive jobs, which can limit outsourcing and offshoring activities. Supplementary, AI, Big Data analytics, ERP, MES, or cloud solutions promote data automation processes. This kind of automation enhances and simplifies decision-making and cognitive tasks. However, thus far, most technologies only unlock competitive advantages at plant level or technological readiness is relatively low. The derived plant-technology-competence framework (figure 12) has shown its strengths for quickly mapping digital technology activities in an IMN. It was discussed with representatives of the case companies and evaluated for being useful and easy to use. The framework can support operation managers who are planning to coordinate the utilization and development of digital technologies in their IMNs. The plant-technology-competence framework can also help identifying redundancies and unwanted activities in an IMN. This can be seen, for example, in the MTC case. Although the company has actively and systematically designed its IMN and site roles, the framework revealed some redundancies that were not intended. Nonetheless, for large IMNs the framework becomes unclear and the advantage of simple mapping and recognizing current setups wanes. In this case, a table might offer a better or at least similar visualization. Hence, a more detailed assessment could further improve the plant-technology-competence framework.

In this regard, this research has identified relevant digital technologies that go beyond single locations and affect whole manufacturing networks. For the case companies, AM, AR, MES, smart robotics, and collaborative robotics have the highest impact on IMNs in terms of automation, cost reduction, quality improvement, and coordination. Consequently, recommendations for application and advantages have been outlined. This offers a fresh view on the utilization of digital technologies from an IMN perspective. Operational and plant managers might make use of these findings to enhance their specific network configuration and coordination levers.

Finally, the study provides additional guidance for technology transfer. Whether a digital technology is rolled out according to *parallel*, *delayed* or *sequential* approaches, a clear procedure (figure 26) has been developed based on the outcomes of the interviews and a comprehensive literature review. This contribution might support companies that are struggling with the transfer of digital technologies. The topic could be further detailed in the view of the "diffusion of innovations" theory (cf. Rogers, 1983).

7.3 Limitations and further research

This research has some limitations that offer potentials for further research. At first, this research is limited to IMNs or intra-firm networks, which largely excludes interactions along the supply chain and with other stakeholders. The narrow object of study allows a more detailed research but ignores important factors of a real world manufacturing environment. As the research is conducted under the umbrella of the RBV and DCV, other theories such as contingency theory could be considered to take on another perspective. The external perspective could holistically extend the internal view on plant roles and network configuration. Having a look at the whole value chain by integrating third parties such as suppliers, customers and other stakeholders in more detail, would offer further opportunities for research.

Likewise, digitalization is only considered from an internal perspective. Changes of IMNs due to new business models, digital sales channels or smart services are not examined in the context of this work. Additionally, the research context is limited to manufacturing companies. Although, nowadays, companies are trying to become "full solution providers", other industries or departments (e.g. service) are not considered. An extension to other fields or the external digitalization perspective could increase the generalizability the findings regarding *lead* factories and high-wage countries even more.

Another limitation is rooted in the methodology of case study research. On the one hand, cross-case research is quite useful in constructing theoretical models and to provide rich information as well as in-depth insights. On the other hand, representativeness and generalizability of the outcomes might be limited due to the small sample. The author is aware of the limitations and tried to enhance the reliability and validity of the case studies. In this context, cases were selected in terms of different industries, sizes, manufacturing footprints, technology applications, and evaluated carefully. Furthermore, triangulation and a systematic iteration process according to chapter 1.5 were applied to optimize single findings and avoid misinterpretations. However, the transferability of the findings cannot be guaranteed. Although the companies selected are leaders in their specific industries and so allow for better comparisons (Barratt et al., 2011, p. 331), an overall explanation for the diverse strategic approaches and technological setups in different industries is not promising due to the limited sample size. Future research could extend the outcomes of this research either in applying more cases (cf. field study) to "extend the study to new populations" (Meredith, 1998, p. 443) or by quantitative analysis to verify and improve the findings. Especially, the derived propositions A to I in chapter 5 could be reviewed. Moreover, the cross-industry case studies at hand are a static observation of the impact of digital technologies on IMNs. As long-term changes are not considered, this only gives a small and temporary fragment of a large picture. Based on the assumption that markets and technologies are continuously changing, a subsequent longitudinal study would be advisable.

Besides, the cases represent companies from Western Europe, namely Germany and Switzerland. Even though these companies have an international footprint with globally dispersed sites, cultural differences and foreign characteristics are not reflected in detail. It would be interesting to add cases from companies in other high-wage countries outside Western Europe (e.g. Japan, Northern America) to verify the research outcomes.

Further research could also address two specific topics, which have come up in the discussions and interviews with the case company's representatives. With increasing implementation and operation of digital technologies, the typical trade-off between time, cost and quality seems to be resolved or at least better addressable. Extended research in this field could investigate what technological solutions are facilitating this development and what the consequences for manufacturing companies and whole IMNs are. Another development in high-wage locations, which was mentioned by the interview partners, is the extension of international footprints by establishing entirely new forms of plants. Companies increasingly operate urban factories (e.g. Audi AG, Wittenstein SE) or customization sites (e.g. Adidas speed factory). The long-term roles, benefits and integration of these sites in IMNs could be examined in further research based on the findings of this thesis.

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Appendix

Appendix A: Journal selection

Table 21: Final journal selection after excluding journals with distinct focus (own illustration)

No.	Journal	Prasad & Babbar (2000)	De Toni & Parussini (2010)	Petersen et al. (2011)	Cheng et al. (2015)	VHB-Jourqual 3 Production	VHB-Jourqual 3 TIE
1	Academy of Management Executive/Perspectives	●					
2	Academy of Management Journal (AMJ)	●		●			
3	Academy of Management Review (AMR)	●		●			
4	California Management Review (CMR)	●			●		
5	Computers and Industrial Engineering (CIE)	●		●		●	
6	Computers and Operations Research (COR)	●		●	●		
7	Computers in Industry					●	
8	Decision Sciences (DS)	●		●		●	
9	Economics of Innovation and New Technology						●
10	European Journal of Operational Research (EJOR)	●		●	●	●	
11	Harvard Business Review (HBR)	●	●	●	●		
12	IEEE Transactions on Engineering Management						●
13	IIE Transactions (IIET)	●		●	●	●	
14	Industrial Engineering (IE)			●			
15	Industry & Innovation						●
16	Integrated Manufacturing Systems		●				
17	Interfaces (IF)	●		●	●	●	
18	International Journal of Automotive Technology and Management					●	●
19	International Journal of Information Technology & Decision Making						●
20	International Journal of Innovation and Technology Management						●
21	International Journal of Operations and Production Management (IJOPM)	●	●	●	●	●	
22	International Journal of Physical Distribution and Logistics Management				●	●	
23	International Journal of Production Economics (IJPE)	●		●	●	●	
24	International Journal of Production Research (IJPR)	●		●	●	●	
25	International Journal of Technology Management						●
26	Journal of Engineering and Technology Management						●
27	Journal of Industrial Engineering (JIE)			●			
28	Journal of International Business Studies (JIBS)	●	●		●		
29	Journal of Management (JOM)	●					
30	Journal of Manufacturing Systems (JMS)			●			
31	Journal of Manufacturing Technology Management (JMTM)		●		●		
32	Journal of Operational Research Society (JORS)	●		●			
33	Journal of Operations Management (JOM)	●	●	●	●	●	
34	Journal of Purchasing & Supply Management (JPSM)		●		●	●	
35	Journal of Supply Chain Management (JSCM)			●		●	
36	Journal of World Business	●					
37	Management Information Systems Quarterly (MISQ)					●	
38	Management Science (MS)	●	●	●	●		
39	Manufacturing & Service Operations Management (M&SOM)					●	
40	Omega (OME)	●	●	●	●		
41	Production and Inventory Management Journal (PIMJ)	●		●			
42	Production and Operations Management (POM)	●	●	●	●	●	
43	Production Planning & Control (PPC)		●		●	●	
44	Research-Technology Management (RTM)						●
45	Sloan Management Review (SMR)	●		●	●		
46	Strategic Management Journal (SMJ)	●		●	●		
47	Supply Chain Management: An International Journal (SCMIJ)				●	●	
48	Technological Forecasting and Social Change					●	●
49	Technology Analysis & Strategic Management						●
50	Technovation						●
51	The Journal of Technology Transfer						●

Appendix B: Database selection

Table 22: Database selection (own illustration)

Database	Time	Search Parameters	Limitations
EBSCOhost	from 2000	All fields	Database "Business Source Premier"; peer reviewed journals; full text
Emerald	from 2000	Title, abstract, keywords	Research paper
ProQuest (ABI/Informs)	from 2000	Title, abstract, keywords	Peer reviewed journals; full text
ScienceDirect	from 2000	Title, abstract, keywords	Journals

The search was conducted on July 10th, 2017 and revised on March 4th, 2018.

Appendix C: Clustering approach for the systematic literature review

Table 23: Keyword search and cluster (own illustration)

	Cluster 1 **Manufacturing network**	Cluster 2 **Configuration**	Cluster 3 **Location**	Cluster 4 **Roles**
	"manufacturing network" OR "production network" OR "IMN"	"manufacturing footprint" OR "production footprint" OR "network configuration"	"plant location" OR "site location" OR "high-wage plant" OR "high-wage site" OR "high-wage location" OR "high-wage factory" OR "high-wage facility"	"plant role" OR "site role" OR "factory role" OR "facility role" OR "subsidiar* role" OR "high-wage role"
Cluster 5: **Digitalization & technology** "technolog*" OR "digitali?ation" OR "digital" OR "industr* 4.0" OR "smart manufacturing" OR "automati*"	AND	AND	AND	AND

Appendix D: Results of literature search

Table 24: Results of literature search (own illustration)

	Cluster				Databases				Total
	1	2	3	4					
	Manufacturing network	**Configuration**	**Location**	**Roles**	EBSCOhost	Emerald	ProQuest (ABI/Informs)	ScienceDirect	
Cluster 5: **Digitalization & technology**	AND				253 (17)	106 (3)	75 (16)	365 (18)	54
		AND			82 (3)	75 (2)	79 (4)	59 (2)	11
			AND		143 (3)	39 (1)	64 (3)	69 (2)	9
				AND	14 (0)	2 (0)	14 (2)	19 (1)	3

Appendix E: Integration of plant and network perspective

Table 25: Overview of integrated plant-network approaches (own illustration)

Authors	Name	Dimension
Colotla et al. (2003)	*Factory-network capability matrix*	▪ Factory-level competitive position ▪ Network-level competitive position ▪ Time
Christodoulou et al. (2007)	*Mountain model*	▪ Configuration and layout of the processes ▪ Process stage ▪ Primary geographic purpose ▪ Activities performed by the site
Miltenburg (2009)	*Manufacturing strategy framework for a manufacturing network*	▪ Factory type ▪ Manufacturing network type ▪ Network manufacturing output ▪ Level of network manufacturing capability ▪ Network manufacturing levers
Asmussen et al. (2009)	*MNE as a diamond network*	▪ Supply competence ▪ Market competence ▪ Technical competence
Feldmann et al. (2013)	*Linking network and plant roles*	▪ Markets ▪ Plants ▪ Level of technical activities
Cheng et al. (2011)	*Network evolution framework*	▪ Geographic dispersion of manufacturing operations ▪ Coordination between the international manufacturing operations ▪ Network learning ability and thriftiness ▪ Network accessibility
Scherrer-Rathje et al. (2014)	*Site classification framework*	▪ Degree of cooperation ▪ Degree of knowledge exchange ▪ Bandwidth of competences ▪ Reach of competences
Thomas et al. (2015)	*Site portfolio*	▪ Accessibility (market, knowledge, low cost) ▪ Scope (bandwidth and reach of competences) ▪ Scale (degree of concentration, production volume) ▪ Mobility (flexibility, degree of duplication) ▪ Learning (Knowledge generation and exchange)

Appendix F: Technology descriptions

Overview and description of the 30 most discussed digital technologies related to manufacturing:

- ***4D printing***

4D printing is a technological advancement of AM or 3D printing. According to Lee, Kim, Choi, & Lee (2017, p. 379), "in a 4D printing system, printed 3D objects have not yet taken their final structures at the time of printing, and the printed objects will change their form over time through external stimulation such as temperature, light, electricity". Thus, the additional dimension here is time. The idea is that 4D printed products can be transported at minimum space and "unfold" at the customer's. Another conceivable application is the medical sector (Shin, Kim, & Kim, 2017, p. 349).

- ***Additive manufacturing***

AM is defined as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM Standard, 2012, p. 2). A frequently used synonym is "3D printing", especially in the context of low-tech machines. The various AM techniques can be classified into solid-based, powder-based and liquid-based processes (Hopkinson & Dickens, 2006, p. 57). In this regard, different materials such as polymers, metals, ceramics, or synthetic resin can be used (Strange & Zucchella, 2017, p. 177). Depending on the technique, the advantages of AM are, among others, reduction of waste, ability to create complex and functionally integrated parts, rapid design changes, accelerated process development, no required tooling, or customized production. While AM was initially used for product development (rapid prototyping), technological developments make it possible to produce final products in small quantities or spare parts (Kang et al., 2016, p. 121). However, these characteristics are actually valid for every modern machine tool and not exclusively for AM.

- ***Artificial intelligence***

Artificial intelligence (AI) began back in the 1950s. Nowadays, it is a collective term for various tools such as neural networks, fuzzy logic, inductive learning, genetic algorithms, or knowledge-based systems (Sanders & Gegov, 2013, p. 184). Although no clear definition of the term AI exists in literature, the following formulation by Rich (1983) is often quoted: "Artificial intelligence is the study of how to make computers do things at which, at the moment, people are better" (cf. Ertel, 2011, p. 2). Hence, AI gives machines and systems the ability to act and make decisions that are normally accomplished by the human mind. Accordingly, the learning ability, often discussed interchangeably with machine learning, is a central subfield of AI.

- ***Augmented reality***

Augmented reality (AR) is a visualization technology to provide additional information visually and expand an operator's perception to assist work activities in real-time (Mekni & Lemieux, 2014, p. 205; Syberfeldt, Holm, Danielsson, Wang, & Brewster, 2016, p. 109). Typical devices are smart glasses, head-mounted displays, traditional monitors, windowpanes, or handheld devices. A new development are spatial solutions that directly project information on an object without any display. All AR solutions combine display technique, tracking as well as real-time rendering (Azuma et al., 2001, p. 34; Siepmann, 2016b, p. 67). According to Kipper & Rampolla (2012, p. 1), "augmented reality is taking digital or computer generated information, whether it be images, audio, video and touch or haptic sensations and overlaying them over in a real-time environment […] AR supplements reality, rather than completely replacing it". Hence, in contrast to virtual reality (VR), AR only extends the real world (Mittal et al., 2017, p. 7). In manufacturing, AR can support assembly or maintenance operations.

- ***Automated guided vehicles***

An autonomous transport system or "automated guided vehicle is a driverless vehicle, whose movement can be controlled by wires, strategically positioned radars, or special tapes. It provides automated loading, transportation, and unloading capabilities" (Ventura, Pazhani, & Mendoza, 2015, p. 850). These automated systems are mainly applied for logistics, warehousing, transportation, or material handling (Fazlollahtabar & Saidi-Mehrabad, 2015, p. 525). Especially tuggers, unit loaders or forklifts in high rack storage are deployed in manufacturing environments. Automated guided vehicles plan their route a priori by scanning the location in advance or analyze the environment dynamically with sensors or laser scanners. For that reason, these systems are ordinarily based on sensor techniques, network models, artificial intelligence, and track & trace technology. Fazlollahtabar & Saidi-Mehrabad (2015, p. 540) and Ventura et al. (2015, p. 851) provide comprehensive overviews of methods for path guiding, routing and scheduling.

- ***Big Data analytics***

The term Big Data refers to "large, diverse, complex, longitudinal, and/or distributed data sets" (Floridi, 2012, p. 435). Big Data analytics has evolved from decision support systems and business intelligence (H. Chen, Chiang, & Storey, 2012, p. 2). It enables companies to analyze data in terms of the 3Vs (*volume, variety, velocity*). *Volume* reflects the issue of large amounts of data that are collected and need to be stored or processed. *Variety* describes the diversity of formats and sources of data fields and *velocity* stands for the frequency of data generation (Gandomi & Haider, 2015). Some authors extended the 3Vs by adding *value* (extracting benefits from data) and *veracity* (trust in data sources) as critical factors (Fosso Wamba, Akter, Edwards, Chopin, & Gnanzou, 2015).

Further, Big Data analytics is "the ability to acquire, store, process and analyze large amount of […] data in various forms, and deliver meaningful information to users that allows them to discover business values and insights in a timely fashion" (Y. Wang, Kung, & Byrd, 2018, p. 6). Thus, Big Data analytics has the potential to support decision-making, create transparency, discover variability, or improve performance (Fosso Wamba et al., 2015, p. 239; Gandomi & Haider, 2015, p. 140). Methods for analyzing such large amounts of data are among others data mining, database management systems, data warehousing, clustering, regression, anomaly detection, neural networks, genetic algorithms, multivariate statistical analysis, or heuristic search (H. Chen et al., 2012, p. 10). Developments of the Big Data topic with regard to applications, data collection, analysis and storage are discussed in detail by Chen, Mao, & Liu (2014).

- ***Blockchain***

Blockchain is cryptographic technology. A blockchain is an aggregation of data packages, so-called blocks. Each block comprises various transactions, a timestamp and is "validated by the network using cryptographic means" (Nofer, Gomber, Hinz, & Schiereck, 2017, p. 184). Each block carries the information about its previous (parent) block and a unique identification number. New transactions create an additional block that extends the blockchain. The existing blocks in the chain must prove the validity of the new transaction before the block is added. Hence, a blockchain is the result of many transactions and functions as a ledger (Nofer et al., 2017). This makes the blockchain a secure solution for different applications such as crypto-currency or traceability along the value chain. So blockchain technology offers the benefits of openness, independence and trust (Morabito, 2017, p. 12).

- ***Cloud computing***

Cloud computing is an on-demand solution for storing data and information in real-time in a virtual "cloud". Major gains of this location-independent data management tool are increasing flexibility and scalability. Having the access authority, centralized information is accessible from each location worldwide (Bruque Cámara, Moyano Fuentes, & Maqueira Marín, 2015, p. 427). Further, cloud computing enables a customized use of IT services as this solution replaces local data storage, servers or software with services offered by external cloud providers. Depending on the use of services, resources (hardware, storage capacities) can be added or cancelled (Cao, Schniederjans, & Schniederjans, 2017, p. 49). Apart from data and information storage, cloud services are "Infrastructure as a service" (IaaS), "Platform as a service" (PaaS) and "Software as a service" (SaaS) (Bruque Cámara et al., 2015, p. 432). A recent attempt is the concept of transferring the on-demand principles of cloud computing to the production environment (cf. cloud manufacturing) (Ren et al., 2015, p. 188).

- ***Cyber-physical systems***

CPS are often discussed synonymously with digital technologies (Hozdić, 2015; Kang et al., 2016; Lee et al., 2015; Monostori, 2014; Obermaier, 2016). These systems are described as "collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services" (Monostori, 2014, p. 9). Therefore, CPS are "integrations of computation with physical processes" (E. A. Lee, 2008, p. 363) and capable of interacting and communicating with the internet or other CPS. Thus, for example, a modern robot, milling machine or other systems can be a CPS. In contrast to IoT objects, CPS do not necessarily need access to or exchange data with the internet (L. Wang & Wang, 2018, p. 35).

- ***Digital/cyber security***

Digital or cyber security encompasses all concepts, measures and tools to protect the cyber (IT) environment of an organization from access by unauthorized third parties. The networked system structures of digitalization with a multitude of interfaces between humans, IT systems and machines offer a large impending area of attack for the misuse or theft of data (Weber & Weber, 2010, p. 1). The threat can come from internal (employees) or external sources such as malicious software (e.g. Trojans) that can be used to access confidential information. Examples are private, financial or know-how data. Measures to reduce the likelihood of a security lack are manifold (Todd & Rahman, 2013).

- ***Digital twin***

A digital twin is a virtual copy of physical and functional attributes of an object along the whole product lifecycle (Cadet et al., 2017, p. 52). Accordingly, a digital twin closes the gaps between different lifecycle phases and provides all information from development stage to the recycling phase. It is defined as "an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin" (F. Tao et al., 2018, p.

3566). Its major characteristics are real-time reflection between the physical object and the digital copy as well as self-evolution as the digital twin continuously adapts dependent on its physical opponent. The concept of digital twins can potentially enhance product design, manufacturing processes and service offerings.

- ***Enterprise Resource Planning***

Enterprise Resource Planning (ERP) is a configurable information technology to support the resource planning and business processes of a company (J. Wu & Wang, 2006, p. 882). This includes data from purchasing, production, sales, finance, or other departments. As mentioned in Jacobs & Weston Jr. (2007, p. 357), ERP is a kind of “framework for organizing, defining, and standardizing the business processes necessary to effectively plan and control an organization so the organization can use its internal knowledge to seek external advantage”. Most ERP systems are developed externally and then adjusted for an individual company. Thus, it is a modular application software. The data is analyzed and stored centrally in a database (J. Wu & Wang, 2006, p. 884).

- ***Hologram***

A hologram is a visualization technology like AR or VR. From a technological perspective, a hologram is a three-dimensional image shaped by light. Such holograms compose billions of pixels, which lead to spatial images of real objects (Matsushima et al., 2013). Although the idea of holograms has been well known for many years, the research outcomes on this technology are rather limited.

- ***Industrial automation***

In this context, industrial automation is understood, on the one hand, as the automated processing of physical objects in manufacturing and assembly operations and, on the other hand, as the automated analysis of data (L. Wu, Yue, Jin, & Yen, 2016, p. 405).

- ***Internet of Things***

The term IoT has already been introduced in chapter 2.6.2. However, IoT is less a single technology but rather a general term for objects that are connected and share information with the internet.

- ***Machine-to-machine communication***

Machine-to-machine communication (M2M) is the automated exchange of information between technical systems such as machines and devices. To communicate, machines use different transmission technologies such as fieldbus, wireless local area network (WLAN), hypertext transfer protocols, transmission control protocols, or serial interfaces. Hence, a fundamental precondition for M2M are communication standards (Siepmann, 2016b, p. 60).

- ***Machine learning***

Machine learning enables a computer or system to further develop itself without being programmed by an operator. In other words, "machine learning refers to an area of computer science in which patterns are derived ("learned") from data with the goal to make sense of previously unknown inputs. As part of both, artificial intelligence and statistics, machine learning algorithms process large amounts of information" (Schuld, Sinayskiy, & Petruccione, 2015, p. 172). Hence, it is part of AI with a distinct focus. Typically, such machines can recognize images, patterns and speech and use it for optimization and further self-evolution. Three approaches, namely supervised, unsupervised and reinforcement learning, are common for machine learning (Schuld et al., 2015, p. 175). In addition, the trial-and-error principle is often applied (Whitehead & Ballard, 1991, p. 46).

- ***Manufacturing Execution System***

A Manufacturing Execution System (MES) is the link between enterprise planning (ERP) and shop floor level (Gerberich, 2011, p. 37). MES systems are integrated, modular and real-time information processing systems that cover the entire manufacturing process (Gerberich, 2011, p. 41; Kletti, 2015, p. 20). According to the latest VDI guideline 5600, an MES system can take over various operational tasks. These are order, equipment, materials, human resources, quality, information and energy management, detailed scheduling and process control, data acquisition, and performance analysis (VDI, 2016). In contrast to the previous, isolated applications, MES integrates and stores data in a single database (Gerberich, 2011, p. 80).

- ***Mobile computing/devices***

Commercial mobile devices (e.g. tablet computers, smartphones) are increasingly employed in manufacturing environments (Morkos et al., 2012, p. 102). They can be used as readers for barcodes, communication tools (audio and video), visualization of manuals and instructions, as mobile notification centers, etc. Pintzos, Rentzos, Papakostas, & Chryssolouris (2014) point out the main advantages and disadvantages of mobile devices and AR. A special form of mobile devices in production are wearables.

- ***Product Lifecycle Management***

Product Lifecycle Management (PLM) systems are business approaches to manage a product effectively along its lifecycle (Saaksvuori & Immonen, 2008, p. 2). It is not an independent technology or self-contained system, but an information management system that incorporates processes, data, humans, and other resources (Pagoropoulos et al., 2017, p. 22). A PLM system provides relevant product information such as bill of material, change orders, production procedures, or test specifications to all stakeholders that are part of the lifecycle. Jupp & Nepal (2014, p. 31) add that PLM in a manufacturing environment has "evolved to provide platforms for the creation, organization, and dissemination of product-related knowledge across the extended enterprise".

- ***Radio Frequency Identification***

RFID belongs to the auto-ID systems (cf. barcodes) and is used for transferring unique identification codes. Technologically it consists of the two components: tag (label) and reader (López et al., 2011, p. 287). RFID tags enable the electronic identification as well as the storage of information. These can be transmitted contactless over a radio frequency channel and only on-demand. In practice, RFID techniques have different reading speeds and ranges. Additionally, a distinction is made between passive, semi-passive and active RFID tags. While passive tags do not have their own power supply and take energy for the operation from the magnetic field of readers, active tags have their own power source. The foremost advantages of RFID are the small sizes of tags, the ability to transfer data over longer distances (e.g. super high frequency), increased storage volume, and its robustness. (Tamm & Tribowski, 2010)

- ***Sensors & actuators***

Sensors are objects to detect and measure physical variables and convert them into electrical, magnetic or mechanical output signals. Available sensors can record parameters such as pressure, acoustic, light, force, voltage, or temperature (López et al., 2011, p. 288). Actuators receive an electrical signal and create a prescribed physical change by motion, force, etc. Sensors and actuators can be selected according to technical (e.g. accuracy, reliability, range, real-time capability, power consumption) or economic (e.g. price) criteria. Both are basic components for other digital technologies such as robotics or wearables.

- ***Smart dust***

Smart dust is the collective term for micro-electromechanical systems, which have a size of a few millimeters. It is a special sensor node form and comprises a power source, wireless transmitter, memory, microcontroller, and one or more sensors (Kahn, Katz, & Pister, 1999, p. 271). As mentioned before, a sensor can measure environmental conditions. This combination of different technical components should allow an object to act autonomously. Although the initial idea of smart dust dates back to the late 1990s, the technology is still immature.

- ***Smart robotics***

Industrial automation enabled by robots has been known for decades. However, “it is only recently that their widespread adoption has become a reality across a range of industries” (Strange & Zucchella, 2017, p. 176). Both traditional robots as well as smart robots are replacing manual and routine workforce. Furthermore, smart robots have the ability to partially substitute non-routine jobs. Frey & Osborne (2017, p. 258) define routine tasks “as tasks that follow explicit rules that can be accomplished by machines, while non-routine tasks are not sufficiently well understood to be specified in computer code. Each of these task categories can, in turn, be of either manual or cognitive nature”. While traditional robots are characterized by performing nearly identical tasks over their lifecycle (operating time 12-16 years) (Lehmann, Städter, & Berger, 2017, p. 45), “smarter robots are putting more skilled professions at risk” (Kowalkiewicz, Safrudin, & Schulze, 2017, p. 49). Smart is defined as “clever and intelligent, i.e. having the ability to make informed decisions on the basis of some available information for one’s own benefit” (López et al., 2011, p. 285). Sensors, M2M, AI, and machine learning (including image and pattern recognition) are the driving forces for robots to become smart (Weng, Chen, & Sun, 2009, p. 268). Consequently, smart robots can perceive their environment, take decisions based on their sensing ability and act physically. This allows them to perform more and more non-routine tasks (Frey & Osborne, 2017, p. 260).

The fields of applications range from warehousing, production, quality control, or assembly to packaging operations (Huber, 2016, p. 52). The vision is an automatic parameterization of assembly lines where smart robots communicate with each other to steer production processes most efficiently. Aside from technological discussions, robot laws, ethics and rights are of increasing interest in academic research (cf. Weng et al., 2009, p. 270).

- ***Collaborative robotics***

Collaborative robotics in manufacturing are a subset of smart robotics. In this case, a collaborative robot becomes an assistant instead of a “competitor” for the employees (Hänisch, 2017, p. 20). The idea of collaborative robots can be summarized as follows: “The ambition is for robotics to become collaborative, intuitive, self-monitoring, agile and relatable, exhibiting human-like characteristics. Ultimately, the vision is to “uncage” robots, enabling them to move on from being traditionally separated from people for safety reasons and allowing them to work alongside their human counterparts” (World Economic

Forum, 2017, p. 14). Whereas traditional robots operate in a secured area, separated from the employees, collaborative robots work side by side with humans without any cages or laser barriers. For this scenario, a collaborative robot has to be “smart” by using AI and machine learning as explained beforehand (Weng et al., 2009, p. 268). It needs to be able to perceive its environment, take decisions and act accordingly to avoid collisions with humans. Inflexible movements are replaced by touch sensitive and image recognition mechanisms to increase safety of employees. The levels of collaborations can be classified into three generic categories. First, robots work “on safe hold” to humans to avoid direct contact (Khalid, Kirisci, Ghrairi, Thoben, & Pannek, 2016, p. 6). Second, an integrated collision detection stops or slows down the robot upon approaching an employee (Kulić & Croft, 2007, p. 158). Third, the robot can touch the employee with a limited, pre-defined force. At present, collaborative robots are predominantly used in assembly operations.

- ***Social media technology***

In general, social media technology is defined “as the forms of electronic communication (as web sites for social networking and microblogging) through which users create online communities to share information, ideas, personal messages, and others (e.g. videos)” (Rauniar, Rawski, Yang, & Johnson, 2014, p. 7). This technology is two-fold for organizations. On the one hand, social media can be used for marketing and sales (social media mining) (Hänisch, 2017, p. 11). On the other hand, social media can be used as a communication technology in organizational processes (Treem & Leonardi, 2013, p. 143). Internal wikis, blogs, chats, or microblogging are applied as recent communication tools to exchange information within a company (Kwai Fun IP & Wagner, 2008, p. 248; Treem & Leonardi, 2013, p. 148). In contrast to traditional email programs, this new media tool accelerates cooperation due to informal and faster exchange of information.

- ***Track & trace***

Track & trace is a technological solution to identify the current and past locations of objects (Mittal et al., 2017, p. 9). This information can be traced (continuously) in real-time. It is a basic element for autonomous guided vehicles.

- ***Unmanned Aerial Vehicles/drones***

Unmanned Aerial Vehicles (UAV) or drones in manufacturing, originally used by militaries, are becoming increasingly interesting for other applications. Drones can operate autonomously or can be controlled precisely by an operator because they have a powerful autopilot. Similar to automated guided vehicles, drones are able to support logistics, quality control, warehousing, transportation, or material handling (Hänisch, 2017, p. 25).

In particular, the distribution of goods is a promising application for manufacturing and commercial industries (Strange & Zucchella, 2017, p. 179). Maghazei & Netland (2017) were among the first who studied drones for the use in manufacturing locations.

- ***Virtual reality***

VR technology is used to create an as realistic as possible computer-formed three-dimensional world. Besides the optical illusion, also the auditory and tactile senses of an operator are addressed. Therefore, “virtual reality allows a user to step through the computer screen into a three-dimensional world. The user can look at, move around, and interact with these worlds as if they were real” (Mujber, Szecsi, & Hashmi, 2004, p. 1835). Thus, the environment and surroundings are completely modelled. For example, VR offers the possibility to create a realistic representation of the production process and simulate it in an interactive way (Siepmann, 2016b, p. 65). VR can be clustered into non-immersive, semi-immersive and fully immersive systems, which depends on the degree of illusion the system provides.

- ***Wearables***

According to Barfield (2016, p. 3), wearable computers can be understood “as a computing device that is small and light enough to be worn on one’s body without causing discomfort”. It can assist an operator by providing context specific information. Wearables are designed to operate them hands-free. This is the major difference to smartphones and other mobile devices. A first classification approach distinguishes between on- or in-body wearables (Barfield, 2016, p. 4). On-body solutions can be further classified into hand- (e.g. smartwatch) or foot-worn (e.g. shoe with tracking function), head-mounted (e.g. augmented reality glasses) or body dressed (e.g. sensor shirt).

Appendix G: Data collection details

Table 26: Case data collection (own illustration)

	Machine tool company (MTC)	**Building equipment company (BEC)**	**Automotive supply company (ASC)**	**Control & automation company (CAC)**	**Electronic equipment company (EEC)**	**Home appliances company (HAC)**
Questionnaire						
Benchmarking "Industrie 4.0"	●		●	●	●	
Benchmarking "Digital technologies"		●	●		●	●
Printed and qualitative data	●	●	●	●	●	●
Interviews						
Number	6	3	5	4	3	3
Participants	COO; Plant manager; Chief procurement officer; Managing director; Head of digital transformation; Strategic planning	Head of global manufacturing; Head production engineering operations; General manager	Director connected manufacturing; VP manufacturing strategies and investment planning; Plant managers; Manufacturing coordination	COO; Head of global production; Head of innovation & technology management; Plant manager	Senior director manufacturing excellence; Digitalization project leader; Plant manager	Division director; Head of production system planning; Plant manager
Workshops						
Number	6	8	9	5	6	3
Participants	COO; Heads of technical units; Head of digital transformation; Strategic planning; Head of R&D; Plant managers; Logistics & order planning; Chief procurement officer; Managing director; Logistics; Head of technical units	Head production engineering operations; Global strategy IT portfolio and MES	Director connected manufacturing; VP manufacturing strategies and investment planning; Plant managers; Business development; VP engineering and manufacturing; Manufacturing coordination; Digitalization manager	Head of innovation and technology management; Head of Industry 4.0 campaign; Head of corporate research and technology; Plant manager; Head plant engineering; Head IT portfolio; Product and application trends; Information management; Corporate communication technology; Qualification	IT manager; Senior director manufacturing excellence; CFO; Digitalization project leader; Plant manager; Director automation; Director manufacturing execution system	Division director; Plant manager; Manufacturing network manager; Industrial engineering
On-site visits (observations)	●	●	●	●	●	●
Focus group						●

Appendix H: Benchmarking questionnaire "Industrie 4.0 – From a management perspective"

Fragebogen

1 Introduction - Welcome

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Industrie 4.0 –
From a Management Perspective

A Benchmarking on Smart Manufacturing

The opportunities and ways of manufacturing are changing worldwide. Different terms like "Internet of Things", "Smart Manufacturing", "Industrie 4.0" or "Industrial Internet" show the diversity of concepts of the future production. But all these visions lead to the same goal: Improving the production, products and services by connecting both physical and cyber world. The digital transformation has already begun and will continue with an extensive impact on the manufacturing industry.
Since its advent as a conceptual idea four years ago, Industrie 4.0 is nowadays a huge phenomenon which affects almost all markets and manufacturing companies. But what is the real impact? Are companies ready for such a fundamental transformation? What is the right timing for investing in Industrie 4.0? What are improvements regarding products and services? And most important, how can the new way of manufacturing influence company's competitiveness?

Our benchmarking project "Industrie 4.0 – From a Management Perspective" focuses on these topics in order to identify and understand Successful Practices. As a participant in the benchmarking you have the unique opportunity to get insights into our research conclusions and – depending on the performance of your Industrie 4.0/Smart Manufacturing activities – being endorsed as a Successful Practice candidate. In contrast to other studies, which focus on technologies like sensors, robots, etc., we, the Institute of Technology Management at the University of St.Gallen (ITEM-HSG), decided to take a look from the management perspective.

Results for free!
The results of the screening phase of this study will be shared with you in form of a free personalized report of all descriptive findings. The analysis will be finished around end of November 2015.

Participation and confidentiality of the data
Your participation is vital to the success of this unique study. Filling out the questionnaire takes around 30 minutes. The time to collect the data (e.g. performance indicators) differs from company to company. The benchmarking study will be conducted according to the International Benchmarking Code of Conduct, that ensures ethical activities of all participants. The company data will be handled with utmost discretion. Company-specific data will not be used without prior approval of the respective company.

For more information about the benefits of the survey for all participants, confidentiality of data, the benchmarking process as well as information about the administrators, please visit *www.tectem.ch/BMI4*

Contact
If you have any questions or want to receive further information, please do not hesitate to contact us.

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Warm-up question:
How far will Industrie 4.0/Smart Manufacturing go?
Please rate the following trade-off decision from the perspective of your company.

Industrie 4.0/Smart Manufacturing is a fad hype	○	○	○	○	○	○	○	Industrie 4.0/Smart Manufacturing will change the manufacturing and production comprehensively

2 Introduction - Teaser

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0.1 We would like to share the results of this benchmarking with you! Please leave your contact data so we can reach you:

First name

Last name

Company

Country

Email

Phone

Job title

3 Introduction - Contact

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0.2 Would you like to answer the questionnaire for your entire company #v_10# or a distinct organizational unit?

To assure the consistency of results, we kindly would like to ask you to answer this entire questionnaire from a suitable perspective: Either your entire company #v_10# or a distinct organizational unit.

Answering for an organizational unit is usually only advisable for large companies that have several business units that are offering distinctly different products to their respective customers.

- #c_0001#
- Business unit / division / subsidiary / etc.: Please specify

0.3 Which industry does #c_0001# operate in?

If more than one category applies, please indicate the most dominant one.

- Automotive
- Aerospace
- Defence
- Electronics
- Energy
- Food
- IT / Software
- Manufacturing & Engineering
- Medical & Pharma
- Optics / Precision Engineering
- Paper / Plastics / Metal
- Textiles & Clothes
- Transportations & Logistics
- Other (Please specify)
- Don't know

4 I General Information - General

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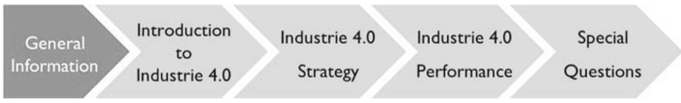
I General Information about #c_0001#



Please provide some general information about #c_0001# for characterization purposes.

I.1 How many people are employed by #c_0001# at all locations worldwide as measured in full-time equivalents?

If you do not have the FTE (full-time equivalent), please provide the number of employees in total. In best case, please provide both.

[ ] [FTE]

[ ] [Employees]

I.2 What type of product are you manufacturing?

Please choose the appropriate answer.

- ☐ Industrial goods (B2B)
- ☐ Consumer goods (B2C)
- ☐ Products / Services for various government levels (B2G)

I.3 How many product lines do you produce?

A product line is a group of products that are closely related to each other by function, customer group, market, or price range. Please indicate the number of product lines.

[ ] Product lines

I.4 Production process uniqueness. Are your processes rather easy or difficult to copy?

Please choose which describes your production process best.

Standard and widely available processes ○ ○ ○ ○ ○ ○ ○ Proprietary and difficult to copy processes

I.5 How long are #c_0001#'s short-term and long-term forecast for production?

Please indicate the number of months for each.

Short-term forecast [ ] [months]

Long-term forecast [ ] [months]

I.6 What does your order-fulfilment strategy look like?

Please choose out of the following alternatives.

- ☐ Engineer-to-order (e.g. a machine specifically designed for one customer)
- ☐ Make-to-order (e.g. a standard machine of given product line produced for a individual customer)
- ☐ Assemble-to-order (e.g. a car - individualised but being only one variety of a mass product)
- ☐ Make-to-stock (e.g. a soap produced for retailing)

I.7 Do you agree with this statement? The following factors are important priorities for #c_0001#.

Please indicate whether you agree or disagree	Strongly disagree						Strongly agree
Cost							
Reduce costs by improving productivity	○	○	○	○	○	○	○
Reduce costs by improving capacity utilization	○	○	○	○	○	○	○
Delivery							
Delivery speed	○	○	○	○	○	○	○
Delivery dependability (On-time-delivery)	○	○	○	○	○	○	○
Quality							
Product durability	○	○	○	○	○	○	○
Conformance quality	○	○	○	○	○	○	○
Reduction of defective	○	○	○	○	○	○	○
Flexibility							
Ability to make rapid design change	○	○	○	○	○	○	○
Broad product line	○	○	○	○	○	○	○
Ability to quickly change product mix	○	○	○	○	○	○	○
Innovativeness							
Increase process innovations	○	○	○	○	○	○	○
Increase product innovations	○	○	○	○	○	○	○

Please rate the importance of each major priorities for #c_0001# by allocating a total of 100 points.

Cost	
Quality	
Delivery	
Flexibility	
Innovativeness	

5 II Introduction to Industrie 4.0

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II Introduction to Industrie 4.0

Please provide some information about #c_0001#'s Industrie 4.0/Smart Manufacturing activities.

II.1 What is your position? Are you provider / supplier of Industrie 4.0/Smart Manufacturing products or user of Industrie 4.0/Smart Manufacturing products?

Please choose the appropriate answer.

- ☐ Provider
- ☐ User

II.2 Which of the following statements most accurately describe #c_0001#'s status regarding Industrie 4.0/Smart Manufacturing?

Please select the relevant statements.

No form of Industrie 4.0/Smart Manufacturing exists today or is under consideration.	☐
We are evaluating Industrie 4.0/Smart Manufacturing solutions.	☐
We are researching on and developing Industrie 4.0/Smart Manufacturing solutions.	☐
We are implementing a specific Industrie 4.0/Smart Manufacturing solution in the production process.	☐
We are selling products produced with Industrie 4.0/Smart Manufacturing.	☐
Use of Industrie 4.0/Smart Manufacturing solutions is decreasing (final life cycle stage).	☐
We are dismantling or have dismantled our Industrie 4.0/Smart Manufacturing activities.	☐

II.3 Since when do you address Industrie 4.0/Smart Manufacturing with projects or initiatives in your company?

Please choose one out of the following alternatives

- ○ Less than 6 months
- ○ 6 months to 1 year
- ○ 1 to 3 years
- ○ 3 or more years
- ○ Not yet, but we plan to do so in the future
- ○ Don't know

II.4 How many people of #c_0001# are dedicated to Industrie 4.0/Smart Manufacturing projects or initiatives at all locations worldwide as measured in full-time equivalents [FTE]?

If you do not have the FTE, please provide the number of employees in total. In best case, please provide both.

________ [FTE]

________ [Employees]

II.5 How many people has #c_0001# explicitly hired or trained for the implementation of Industrie 4.0/Smart Manufacturing activities (as measured in full-time equivalents [FTE])?

If you do not have the FTE, please provide the number of employees in total. In best case, please provide both.

________ [FTE]

________ [Employees]

II.6 What does #c_0001#'s Industrie 4.0/Smart Manufacturing approach look like?

Please pick the most dominant alternative.

- ○ No specified approach
- ○ Top-down: Integrated concept (masterplan to organise all Industrie 4.0/Smart Manufacturing activities)
- ○ Bottom-up: Single projects / initiatives (step-by-step approach)

○ Down-up: Combination of top-down & bottom-up

II.7 How do you deal with the following Industrie 4.0/Smart Manufacturing solutions?

Please check all that apply.

	Not interested	We are researching and developing	Working on the implementation	Already in use for production	Could be interesting in the future	Don't know	We are using an industry standard
3-D Printing	☐	☐	☐	☐	☐	☐	☐
Augmented Reality Solutions (e.g. Digital Glasses)	☐	☐	☐	☐	☐	☐	☐
Autonomous vehicles or transport systems	☐	☐	☐	☐	☐	☐	☐
Cloud Computing	☐	☐	☐	☐	☐	☐	☐
Connected sensors	☐	☐	☐	☐	☐	☐	☐
Inline measure and inspection system	☐	☐	☐	☐	☐	☐	☐
Mass customization	☐	☐	☐	☐	☐	☐	☐
Machine-to-machine communication	☐	☐	☐	☐	☐	☐	☐
Mobile Devices in the production (e.g. Tablet, Smartphone)	☐	☐	☐	☐	☐	☐	☐
Remote Services	☐	☐	☐	☐	☐	☐	☐
RFID and/or NFC (Near Field Communication)	☐	☐	☐	☐	☐	☐	☐
Smart Robots	☐	☐	☐	☐	☐	☐	☐
Social Networks Analysis	☐	☐	☐	☐	☐	☐	☐
Track & Trace	☐	☐	☐	☐	☐	☐	☐

If you are working on other solutions, please mention them:

II.8 What are your highest-grossing products or product categories related to Industrie 4.0/Smart Manufacturing?

Please list the appropriate products and/or product categories.

II.9 Do you agree with this statement? #c_0001#'s Industrie 4.0/Smart Manufacturing activities have a positive impact on the

Please indicate whether you agree or disagree.	Strongly disagree						Strongly agree
Cost							
Reduce costs by improving productivity	○	○	○	○	○	○	○
Reduce costs by improving capacity utilization	○	○	○	○	○	○	○
Delivery							
Delivery speed	○	○	○	○	○	○	○
Delivery dependability (On-time-delivery)	○	○	○	○	○	○	○
Quality							
Product durability	○	○	○	○	○	○	○
Conformance quality	○	○	○	○	○	○	○
Reduction of defective	○	○	○	○	○	○	○
Flexibility							
Ability to make rapid design change	○	○	○	○	○	○	○
Broad product line	○	○	○	○	○	○	○
Ability to quickly change product mix	○	○	○	○	○	○	○
Innovativeness							
Increase process innovations	○	○	○	○	○	○	○
Increase product innovations	○	○	○	○	○	○	○
Other							
Generate additional sales	○	○	○	○	○	○	○
Reduce cost of poor quality	○	○	○	○	○	○	○
Increase margins	○	○	○	○	○	○	○
Increase productivity	○	○	○	○	○	○	○
Offering (more) individualised products	○	○	○	○	○	○	○
Increase transparency and improve decision making	○	○	○	○	○	○	○

II.10 Which are barriers for the successful execution of Industrie 4.0/Smart Manufacturing activities and which of them have you already overcome?

Please select the options that apply.

	Barrier	**Already overcome**
Budget restrictions	☐	☐
Time pressure	☐	☐
Shortage of manpower	☐	☐
Lack of capabilities	☐	☐
Too expensive technologies	☐	☐
Existing infrastructure restrictions	☐	☐
Technical feasibility	☐	☐
Missing norms and standards	☐	☐
IT security	☐	☐
Lack of management commitment	☐	☐
Resistance of the employees	☐	☐
Bad timing (too early)	☐	☐
Bad timing (too late)	☐	☐
Doesn't match with #c_0001#	☐	☐

6 III Industrie 4.0 Strategy

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III Strategy

In this section, we will ask you some questions about your Industrie 4.0/Smart Manufacturing strategy.

III.1 How do you define Industrie 4.0/Smart Manufacturing in your company?

Please give a brief description of what role Industrie 4.0/Smart Manufacturing has at your company and how it is understood.

III.2 What elements of #c_0001#'s business model are addressed by #c_0001#'s Industrie 4.0/Smart Manufacturing strategy?

Please select which elements are addressed.

	Not at all addressed						Completely addressed	Don't know
Customer segments (i.e. serve one or multiple other / new customer segment)	○	○	○	○	○	○	○	○
Customer relationship (i.e. change the way you interact with your customers)	○	○	○	○	○	○	○	○
Channels (i.e. use new communication and sales channels)	○	○	○	○	○	○	○	○
Value Proposition (i.e. the bundle of products or services you offer)	○	○	○	○	○	○	○	○
Key resources (i.e. the resources you need to offer your value proposition)	○	○	○	○	○	○	○	○
Key activities (i.e. the most important activities for your company success)	○	○	○	○	○	○	○	○
Key partners (i.e. your suppliers and partners)	○	○	○	○	○	○	○	○
Cost structure (i.e. the costs generated for your value proposition)	○	○	○	○	○	○	○	○
Revenue streams (i.e. the different ways you earn money with your value proposition)	○	○	○	○	○	○	○	○

III.3 What is the purpose of your current Industrie 4.0/Smart Manufacturing activities?

Please pick all the alternatives that are relevant.

- ☐ Increase production efficiency
- ☐ Keep production in a high-wage country
- ☐ Relocating production to a high-wage country
- ☐ Better enforce existing business model
- ☐ Slightly adapt existing business model
- ☐ Create new business model
- ☐ Other

III.4 Do you collaborate with the following stakeholders in context of Industrie 4.0/Smart Manufacturing and how important are they?

Please check all that apply.

- ☐ Suppliers
- ☐ Customers
- ☐ Competitors
- ☐ Consultants
- ☐ Research institutes / Universities

☐ Associations

☐ Unions / Work council

Please rate the importance of the respective collaboration.

	Very unimportant						Very important	Don't know
Suppliers	○	○	○	○	○	○	○	○
Customers	○	○	○	○	○	○	○	○
Competitors	○	○	○	○	○	○	○	○
Consultants	○	○	○	○	○	○	○	○
Research institutes / Universities	○	○	○	○	○	○	○	○
Associations	○	○	○	○	○	○	○	○
Unions / Work council	○	○	○	○	○	○	○	○

III.5 How do the aforementioned stakeholder(s) contribute to your Industrie 4.0/Smart Manufacturing activities?

Please check all that apply.

	Provide us with information	**Prototyping**	**Commissioned Research**	**Joint Research**	**Provide complete Industrie 4.0/Smart Manufacturing solutions**
Suppliers	☐	☐	☐	☐	☐
Customers	☐	☐	☐	☐	☐
Competitors	☐	☐	☐	☐	☐
Consultants	☐	☐	☐	☐	☐
Research institutes / Universities	☐	☐	☐	☐	☐
Associations	☐	☐	☐	☐	☐

III.6 How many Industrie 4.0/Smart Manufacturing projects have you finished in the last three years / are currently going on?

Please fill in the exact number if possible. If you do not have the exact number, please give your best estimate.

Finished Industrie 4.0/Smart Manufacturing projects ________

Ongoing Industrie 4.0/Smart Manufacturing projects ________

III.7 Which of the following functions are typically represented in #c_0001#'s Industrie 4.0/Smart Manufacturing projects and who should be?

In case #c_0001# didn't work on an Industrie 4.0/Smart Manufacturing project yet, please just indicate which functions are best to be part of such a project team.

	Typically represented	**Should be represented**	**Typically initiates I4.0 projects**
Top Management	☐	☐	☐
Plant Manager	☐	☐	☐
R&D	☐	☐	☐
Production	☐	☐	☐
Supply Chain & Logistics	☐	☐	☐
Quality	☐	☐	☐
Work safety	☐	☐	☐
IT	☐	☐	☐
Sales	☐	☐	☐
Marketing	☐	☐	☐
Finance	☐	☐	☐
Human Resources	☐	☐	☐
Other	☐	☐	☐

III.8 In which locations did #c_0001# already start with the implementation of Industrie 4.0/Smart Manufacturing activities

Please check all that apply and state the location of your headquarter.	**Today**	**In the future**
Headquarter	☐	☐
Western Europe	☐	☐
Eastern Europe	☐	☐
USA / Canada	☐	☐
Middle & South America	☐	☐
China	☐	☐
Japan	☐	☐
Rest of Asia	☐	☐
Africa	☐	☐
Australia & Oceania	☐	☐

Location of Headquarter: ______

III.9 How does #c_0001# develop Industrie 4.0/Smart Manufacturing solutions?

Please choose one out of the two following alternatives.

- ○ Each site develops its own ideas and solutions.
- ○ One site develops Industrie 4.0/Smart Manufacturing solutions and provides them to other company sites.
- ○ One site develops Industrie 4.0/Smart Manufacturing solutions, but in addition each site can work on solutions individually.
- ○ Don't know

7 IV Industrie 4.0 Performance

Introduction » General Information » Introduction to Industrie 4.0 » Strategy » **Performance** » Special Questions

IV Performance

Please give us some numbers about your company as well as an assessment of how you compare to your competition. We know this section is quite challenging, so if you do not know the exact numbers, please provide your best estimate. For some indicated question, please give an estimate of whether you are performing better, the same, or worse than your competition as well.

IV.1 What percentage of #c_0001#'s revenue is spent for Industrie 4.0/Smart Manufacturing activities?

If you do not have the exact number, please give your best estimate.

Average of last 3 years		%
This year		%
Next year		%
Average of next 3 years		%

IV.2 How is #c_0001#'s financial performance compared to its competitors?

Please provide #c_0001#'s overall performance compared to your competitors.

	Much worse			Almost the same			Much better	Don't know
Revenue in last financial year	○	○	○	○	○	○	○	○
EBIT-margin in last financial year	○	○	○	○	○	○	○	○
Change in revenue in the last 3 years	○	○	○	○	○	○	○	○
Change in EBIT-margin in the last 3 years	○	○	○	○	○	○	○	○
Change in market share in the last 3 years	○	○	○	○	○	○	○	○

Please provide #c_0001#'s performance for the products produced with the help of Industrie 4.0/Smart Manufacturing solutions (compared to your conventionally produced products).

Revenue in last financial year	○	○	○	○	○	○	○	○
EBIT-margin in last financial year	○	○	○	○	○	○	○	○
Change in revenue in the last 3 years	○	○	○	○	○	○	○	○
Change in EBIT-margin in the last 3 years	○	○	○	○	○	○	○	○
Change in market share in the last 3 years	○	○	○	○	○	○	○	○

IV.3 How did #c_0001#'s overhead costs develop since you started with your Industrie 4.0/Smart Manufacturing activities?

Please provide the development in percentage (e.g. +12% or -12%). If you do not have the exact number, please give your best estimate.

Change of overhead costs ______ %

IV.4 Which of the following statements describe #c_0001#'s changing productivity since implementing Industrie 4.0/Smart Manufacturing activities?

Please check all that apply.

- ☐ More products produced with less/same direct labour hours.
- ☐ More products produced with less/same machine hours.
- ☐ More products produced with less/same raw materials.
- ☐ More products produced with less/same energy consumption.
- ☐ More products produced with less/same indirect labour hours (overhead).
- ☐ None of the above apply.

IV.5 Are you able to gather production and product information in real-time?

Please choose one out of the two following answers.

- ○ No
- ○ Yes

If yes, how many KPIs can be ascertained in real-time?

[ ] KPI's

IV.6 Which Key Performance Indicators (KPIs) do you use to evaluate an Industrie 4.0/Smart Manufacturing project?

Please check all that apply.

- ☐ Project was finished on-time
- ☐ Project was finished on-budget
- ☐ Technical goals fulfilled
- ☐ Financial goals fulfilled
- ☐ Quality goals fulfilled
- ☐ Strategic goals fulfilled
- ☐ Customer satisfaction
- ☐ Employee satisfaction
- ☐ Other

8 V Special Questions

Introduction » General Information » Introduction to Industrie 4.0 » Strategy » Performance » **Special Questions**

V Special Questions

In this last section, we ask you some questions about technology, humans & management and your customers in the context of Industrie 4.0/Smart Manufacturing.

Technology

V.1 Smart products offer several opportunities. Which of the following are currently used / will be used by #c_0001#?

We distinguish between active (e.g. product tells machine what to do) and passive (e.g. product collects information about its transport history) data. Please check all that apply.

	Currently used	Planned in the future	Don't know
Active production data (e.g. product tells robot what to do with it)	☐	☐	☐
Passive production data (e.g. product memorises the ID of a component attached to it)	☐	☐	☐
Active logistics data (e.g. product tells packaging machine how to wrap it)	☐	☐	☐
Passive logistics data (e.g. product memorises details about the distribution cold chain)	☐	☐	☐
Active application data (e.g. product tells operator how to be handled)	☐	☐	☐
Passive application data (e.g. product memorises how it was treated for guarantee claims)	☐	☐	☐

V.2 Do you use Cloud Computing as a service to save and analyse data?

Please choose one out of the two following answers.

○ No
○ Yes

If yes, do you share the data with the following stakeholders?

☐ Suppliers
☐ Customers
☐ Competitors
☐ Third party platform

Do you plan to use Clound Computing in the future?

○ No
○ Yes

V.3 Production machines are the basis for Industrie 4.0/Smart Manufacturing. How old are #c_0001#'s production machines in average?

If you do not have the exact number, please give your best estimate.

[ ] [years]

How many of your existing machines will #c_0001# replace in the next three years by machines ready for Industrie 4.0/Smart Manufacturing?

None ○ ○ ○ ○ ○ ○ ○ All of them

V.4 What is the link between Industrie 4.0/Smart Manufacturing and #c_0001#'s production system?

A production system is a subsystem that includes all functions required to design, produce, distribute, and service a manufactured product. It can include different principles like LEAN, etc. The most famous example is the Toyota Production System (TPS).
Please choose one out of the following alternatives.

○ We don't have a production system.
○ There is no link, Industrie 4.0/Smart Manufacturing and production systems are stand-alone.

- Industrie 4.0/Smart Manufacturing is integrated in our existing production system.
- Our production system is adjusted to incorporate Industrie 4.0/Smart Manufacturing principles.
- Don't know

V.5 What does #c_0001# expect to be the most promising future scenario?

Please choose one out of the following alternatives.

- Industrie 4.0/Smart Manufacturing dominates the production in the future.
- LEAN principles dominate the production in the future.
- Industrie 4.0/Smart Manufacturing and LEAN are coexisting principles in the future.
- Neither Industrie 4.0/Smart Manufacturing nor LEAN will be dominating principles in the future.
- Don't know

Please choose one out of the following alternatives.

- LEAN enables Industrie 4.0/Smart Manufacturing.
- Industrie 4.0/Smart Manufacturing enables LEAN.
- Don't know

V.6 From #c_0001#'s perspective, is it advisable to execute R&D and production in different locations?

Please check one of the answers listed below.

- No
- Yes

Will this change due to Industrie 4.0/Smart Manufacturing?

- No
- Yes

Human Resources & Management

V.7 How do you manage communication about Industrie 4.0/Smart Manufacturing in your company?

Please indicate how you increase the employee's acceptance concerning Industrie 4.0/Smart Manufacturing.

- ☐ No communication about Industrie 4.0/Smart Manufacturing.
- ☐ Superficial communication (e.g. article in internal magazine or circular mail with general content).
- ☐ Top-down communication of company's specific Industrie 4.0/Smart Manufacturing activities (e.g. presentations).
- ☐ Dialogue between employees and management (e.g. open discussion, panels).
- ☐ Active integration of all employees to develop joint solutions in context of Industrie 4.0/Smart Manufacturing.
- ☐ #c_0001# has a dedicated employee for Industrie 4.0/Smart Manufacturing related communications.

V.8 What are future professionals needed for the realisation of Industrie 4.0/Smart Manufacturing and what are fundamental skills for the implementation?

Please name 2-3 categories of professionals (e.g. production engineer, data scientist).

What skills come to your mind in context of Industrie 4.0/Smart Manufacturing activities.

V.9 Which of the following elements of #c_0001#'s culture did change due to Industrie 4.0/Smart Manufacturing activities?

Please check all that apply, in case there have been changes.

- ☐ No changes
- ☐ Mission statement
- ☐ Stories & Language
- ☐ Control system
- ☐ Rules & Policies
- ☐ Power structures

☐ Organizational structures

☐ Other

V.10 Did the leadership structure of #c_0001# change due to Industrie 4.0/Smart Manufacturing and what are #c_0001#'s expectations about the future?

Please choose one out of the four alternatives.

	Today	In the future
No changes	○	○
Certain changes	○	○

If yes, please describe how the leadership structure changed:

V.11 How would you evaluate the employees' satisfaction with #c_0001#'s Industrie 4.0/Smart Manufacturing activities?

Please give your best estimate.

Very dissatisfied			Neutral			Very satisfied	Don't know
○	○	○	○	○	○	○	○

V.12 How would you evaluate the suppliers' satisfaction with #c_0001#'s Industrie 4.0/Smart Manufacturing activities?

Please give your best estimate.

Very dissatisfied			Neutral			Very satisfied	Don't know
○	○	○	○	○	○	○	○

V.13 How would you evaluate the unions' / work councils' satisfaction with #c_0001#'s Industrie 4.0/Smart Manufacturing activities?

Please give your best estimate.

Very dissatisfied			Neutral			Very satisfied	Don't know
○	○	○	○	○	○	○	○

Customers

V.14 How would you evaluate the customers' satisfaction with #c_0001#'s Industrie 4.0/Smart Manufacturing activities?

Please give your best estimate.

Very dissatisfied			Neutral			Very satisfied	Don't know
○	○	○	○	○	○	○	○

V.15 Do you agree with this statement? Our customers are very satisfied with the following aspects of our products or services enabled by Industrie 4.0/Smart Manufacturing.

Please indicate whether you agree or disagree.

	Strongly disagree						Strongly agree
Price	○	○	○	○	○	○	○
Delivery speed	○	○	○	○	○	○	○
On-time-delivery	○	○	○	○	○	○	○
Quality	○	○	○	○	○	○	○
Flexibility	○	○	○	○	○	○	○
Innovativeness	○	○	○	○	○	○	○
Offering (more) indiviualised products	○	○	○	○	○	○	○
Increased transparency and improved decision making	○	○	○	○	○	○	○

9 End - Successful Companies

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Last question about Industrie 4.0 and Smart Manufacturing

When you think of the most successful companies dealing with Industrie 4.0/Smart Manufacturing in production, which companies come to your mind?

Mentioned companies might be within your industry or even in completely different industries.

	Company name	Reason
1		
2		
3		

10 End

Introduction » General Information » Introduction to Industrie 4.0 » Strategy » Performance » Special Questions

End of survey

Thank you for taking part in this survey!

FOR YOUR INFORMATION:
We also offer reports in an individual dataset for companies that would like to analyse and compare several subsidiaries or business units! Don't hesitate to contact us for more information.

Feedback
We constantly strive for improvement! Please answer the following questions in order to help us do so.

How would you judge the questionnaire?

Too short	○	○	○	○	○	○	○	Too long
Too imprecise	○	○	○	○	○	○	○	Too detailed
I had no problem understanding any of the questions	○	○	○	○	○	○	○	I had problems understanding a majority of the questions

Do you have any further questions or remarks?

Are you interested in information on any further projects of the Institute of Technology Management?

- ☐ General information about projects of ITEM-HSG
- ☐ Funded industry and research projects (e.g. CTI, EU)
- ☐ "Success in the Future of Smart Services" Benchmarking
- ☐ Operational Excellence Cross-Industry Benchmarking (OPEX 2020)
- ☐ *Management Workshop "Industrie 4.0 - A Management Approach"* *

* The objective of the workshop is to deepen understanding of how to deal with Industrie 4.0/Smart Manufacturing as a provider and user. Furthermore, individual implications from this should be derived and connections between participants established, which is leading to a lasting network of experts. Contents of the workshop will be:

- Presentation of a successful practice case from the benchmarking
- Reflection of top-learnings from the benchmarking as well as scientific insights
- Discussion of the results and future trends among attending experts
- Derive valuable insights and individual implications for your business

During the seminar you will be able to connect with some of the leaders in the field of Industrie 4.0/Smart Manufacturing and grow your personal network.

For more information, please check our booklet: www.tectem.ch/BMI4

11 Endseite

Thank you for your participation!

Appendix I: Benchmarking questionnaire "Digital technologies – Evolution of production in high-wage countries"

Fragebogen

1 Language Selection

Herzlich Willkommen zum Benchmarking "Digitale Technologien - Evolution of production in high-wage countries"!
Welcome to our Benchmarking "Digital Technologies - Evolution of production in high-wage countries"!

Bitte wählen Sie eine Umfragesprache. *Please select your language.*

German
English

2 Introduction

Introduction *>> Organization >> Technology >> Strategy >> Stakeholder >> Investments & Performance >> End*

Welcome to our Benchmarking Project "Digital Technologies"!

A project by the ITEM-HSG division of Production Management

The ways of **manufacturing** are changing and improving worldwide. Besides **automation**, the degree of **connecting systems** and the use of **artificial intelligence** in manufacturing are moving forward. These activities are often classified under the keywords **digital/smart manufacturing** or **Industry 4.0**. The **boundary between manufacturing and IT companies is therefore blurred** more and more. Hence, we designed this benchmarking project in a way so that not only manufacturing but also non-manufacturing companies are able to participate and to state their experience regarding digitalization within certain areas. Instead of manufacturing, we use the term operations in their case.

The results of our survey with regard to **use cases** and **developments** shall – according to the benchmarking title **"Digital Technologies – Evolution of production in high-wage countries"** – lead to new insights, approaches and opportunities, especially for manufacturing companies in high-wage countries. Overall, however, the study addresses companies from all industries and regions. The **objective** is to identify **"Successful Practice"** companies, which employ digital technologies in their area in an outstanding way.

Your benefits as a participant
- **Customized final report** for your company (Example: Big Data Study)
- **Compare** your performance to companies within your **industry** and to the **"Successful Practices"**
- Levers and ideas for **improving** your business with regard to **digital technologies** and **smart manufacturing**
- Depending on your performance you might be chosen as "Successful Practice" candidate
  - In this case you have the possibility to **visit other "Successful Practice" companies**
  - On this occasion you **get into contact** with other executives and experts from industry and science (networking)
  - Furthermore you discuss **challenges and opportunities** as well as new **approaches** for your business

Confidentiality

All data is treated confidentially by the University of St.Gallen and is not given to third parties. In addition, we comply with the „International Benchmarking Code of Conduct", which is based on the widely used APQC/SPI Code of Conduct.

Let us shape the future of digital manufacturing together!

Contact Information

For receiving an individualized report, please insert your contact details:

Title

Mr
Ms

First name

Surname

Company

Position

Email Address

Phone

Would you like to answer the questionnaire for the entire company, a specific business unit or a single location?

To ensure the consistency of the results, we kindly ask you to answer the questionnaire either for the whole company or a distinct part of the company.

- ○ Entire company
- ○ Business unit / division / location / etc. - Please specify:

How would you primarily classify your company or business unit?

In order to keep the questionnaire as short as possible, certain questions will be adapted to your company profile according to your selection.

- ○ Manufacturing industry (production of goods)
- ○ IT & Internet business
- ○ Financial and insurance services
- ○ Others

3 Organization

*Introduction >> **Organization** >> Technology >> Strategy >> Stakeholder >> Investments & Performance >> End*

Which industry does #c_0001# operate in?

Please tick the industrial sector, in which your company is operating. If more than one category is correct, please choose the most dominant one.

- 10 - Manufacture of food and animal feed
- 11 - Manufacture of beverages
- 12 - Manufacture of tobacco products
- 13 - Manufacture of textiles
- 14 - Manufacture of clothes
- 15 - Manufacture of leather and related products and shoes
- 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
- 17 - Manufacture of pulp, paper and paper products
- 18 - Publishing, printing and reproduction of recorded media
- 19 - Manufacture of coke and refined petroleum products
- 20 - Manufacture of chemical products
- 21 - Manufacture of pharmaceuticals
- 22 - Manufacture of rubber and plastic products
- 23 - Manufacture of other non-metallic mineral products
- 24 - Metal production and metal processing
- 25 - Manufacture of metal products
- 26 - Manufacture of computer, electronic and optical products
- 27 - Manufacture of electrical equipment
- 28 - Mechanical engineering
- 29 - Manufacture of automotive and automotive components
- 30 - Manufacture of other transport equipment
- 31 - Manufacture of furniture
- 33 - Repair and installation of machinery and equipment
- 32 - Production of other goods, namely:

How would you classify #c_0001#? Are you user or provider (or both) of digital technologies/solutions?

Please choose the appropriate answer.

- Provider
- User

How many people are employed by #c_0001# as measured in full-time equivalents?

If you do not have the exact number, please give your best estimate. Please provide a whole number and do not make use of a separator for thousands.

[FTEs]

What is the primary type of goods produced by #c_0001#?

Please choose one option.

- Consumer goods (B2C)
- Industrial goods (B2B)
- Goods for public institutions (B2G)

Which concept for order processing is primarily applied by #c_0001#?

Please choose one option.

- ○ Make-to-Stock
- ○ Assemble-to-Order
- ○ Make-to-Order
- ○ Engineer-to-Order

How has #c_0001# primarily organized its digitalization activities/responsibilities and how does it plan to adapt it? What do you think is the optimal organizational structure?

You can find an explanation for the organizational structures here. If no changes are planned, please select the same organizational structure for "current" and "planned".

	Current	Planned	Optimal
Organizational structure	<span style="color:#BDBDBD"> Decentralized Functional Project Team Centre of Excellence (Competenc Lead Factory	<span style="color:#BDBDBD"> Decentralized Functional Project Team Centre of Excellence (Competenc Lead Factory	<span style="color:#BDBDBD"> Decentralized Functional Project Team Centre of Excellence (Competenc Lead Factory

What is the role of the IT department at #c_0001# regarding the digitalization of production?

Please indicate to what extent the following statements apply.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
Provision of IT and telecommunications equipment	○	○	○	○	○	○	○	○
Development of digitalization use cases	○	○	○	○	○	○	○	○
Management of digitalization projects	○	○	○	○	○	○	○	○
Implementation responsibility for digital technologies	○	○	○	○	○	○	○	○
Problem solving in production (e.g. defect robot)	○	○	○	○	○	○	○	○
Specification of guidelines (data protection / IT security)	○	○	○	○	○	○	○	○
Auditing (data protection / IT security)	○	○	○	○	○	○	○	○

How many digitalization use cases and projects has #c_0001# finished in the last three years and how many are currently running? How many results from projects have been established as lasting solutions or are now part of the strategy?

Please fill in the exact number, if possible. If you do not have the exact number, please give your best estimate.

Number of on-going digitalization projects

Number of finished digitalization projects

Number of finished digitalization projects, *whose results the company permanently uses*

Have digitalization approaches of #c_0001# won an award or have they been published in an article?

Please choose the appropriate answer.

- ○ No
- ○ Yes, approaches or solutions have been published
- ○ Yes, we received one or multiple award(s)
- ○ Yes both, approaches or solutions have been published and we received one or multiple award(s)
- ○ I don't know

4 Technology

*Introduction >> Organization >> **Technology** >> Strategy >> Stakeholder >> Investments & Performance >> End*

What is the current status of #c_0001# regarding the following technologies, which can be used for Industry 4.0 and digitalization activities?

Please choose one or more options from the list.

	Implementation failed	Not relevant	Observing	Researching and developing	Working on the implementation (Prototyping)	Already in first use	Fully implemented	I don't know
Additive Manufacturing (3-D Printing)	○	○	○	○	○	○	○	○
Augmented Reality solutions	○	○	○	○	○	○	○	○
Autonomous vehicles or transport systems	○	○	○	○	○	○	○	○
Big Data Analytics	○	○	○	○	○	○	○	○
Blockchain	○	○	○	○	○	○	○	○
Cloud Computing	○	○	○	○	○	○	○	○
Digital Twin (Product)	○	○	○	○	○	○	○	○
Digital Twin (Process)	○	○	○	○	○	○	○	○
Drones (Commercial UAWs)	○	○	○	○	○	○	○	○
Identification- or communication solutions (RFID, NFC, etc.)	○	○	○	○	○	○	○	○
Artificial intelligence (AI) or machine learning	○	○	○	○	○	○	○	○
Manufacturing Execution System (MES)	○	○	○	○	○	○	○	○
Machine-to-machine communication (M2M)	○	○	○	○	○	○	○	○
Mobile devices in the production (e.g. Tablet, Smartphone)	○	○	○	○	○	○	○	○
Robotics	○	○	○	○	○	○	○	○
Others: ______	○	○	○	○	○	○	○	○

How important is the use of digital technologies for #c_0001#'s daily business in the following areas?

Please choose the appropriate answer.

	Unimportant	Less important	Little important	Relatively important	Fairly important	Very important	Crucially important	I don't know
Research & Development	○	○	○	○	○	○	○	○
Forecasting & Scheduling	○	○	○	○	○	○	○	○
Production	○	○	○	○	○	○	○	○
Assembly	○	○	○	○	○	○	○	○
Quality assurance & management	○	○	○	○	○	○	○	○
Intra-logistics	○	○	○	○	○	○	○	○
External logistics	○	○	○	○	○	○	○	○
Maintenance	○	○	○	○	○	○	○	○
Service	○	○	○	○	○	○	○	○

What percentage of #c_0001#'s production processes is controlled automatically?

Please choose one option. If you do not have the exact number, please give your best estimate.

- ○ 0 - 20% (almost all manual)
- ○ 21 - 40%
- ○ 41 - 60%
- ○ 61 - 80%
- ○ 81 - 100 % (almost all automated)
- ○ I don't know

What percentage of #c_0001#'s machines and systems are connected and are able to communicate with each other?

Please choose one option. In case you do not know the share, please give a realistic assumption.

- ○ 0 - 20% (overall low connected machine landscape)
- ○ 21 - 40%
- ○ 41 - 60%
- ○ 61 - 80%
- ○ 81 - 100% (overall closely connected machine landscape)
- ○ I don't know

How important are the following factors for #c_0001# as the basis for digitalization activities?

Please choose one or more options from the list.

	Unimportant	Less important	Little important	Relatively important	Fairly important	Very important	Crucial important	I don't know
High level of standardization	○	○	○	○	○	○	○	○
Established lean concept	○	○	○	○	○	○	○	○
Receptive culture	○	○	○	○	○	○	○	○
Top-management support	○	○	○	○	○	○	○	○
Employee commitment	○	○	○	○	○	○	○	○
Qualified employees	○	○	○	○	○	○	○	○
Digitalization rooted in strategy	○	○	○	○	○	○	○	○
Fitting infrastructure	○	○	○	○	○	○	○	○
Availability of data	○	○	○	○	○	○	○	○
Data harmonization	○	○	○	○	○	○	○	○
Cooperation with stakeholders	○	○	○	○	○	○	○	○
Process owner is also responsible for digitalization activity	○	○	○	○	○	○	○	○

How would you evaluate the following statements regarding "interfaces between digital systems"?

Please indicate to what extent the following statements apply.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
We are actively working on the **elimination of interfaces** (e.g. primarily the same solution provider).	○	○	○	○	○	○	○	○
We **overcome interfaces** with our own software solutions.	○	○	○	○	○	○	○	○
We use **industry standards** everywhere.	○	○	○	○	○	○	○	○
When purchasing new systems, we pay particular attention to **compatibility with our existing systems**.	○	○	○	○	○	○	○	○
Data exchange between systems is **not relevant** to us.	○	○	○	○	○	○	○	○
Data between incompatible systems is transferred **manually** by our employees.	○	○	○	○	○	○	○	○

4.1 Technology (gefilterte)

*Introduction >> Organization >> **Technology** >> Strategy >> Stakeholder >> Investments & Performance >> End*

How would you classify #c_0001# regarding its use of manufacturing or operations data?

Please indicate on which stage you consider your data analytics capabilities. You can find an explanation here.

- ○ *Not in use*
- ○ **Descriptive** ("What happened?")
- ○ **Diagnostic** ("Why did it happen?")
- ○ **Predictive** ("What is likely to happen?")
- ○ **Prescriptive** ("What should be done?")

In which of the following areas does #c_0001# make use of advanced big data analytics?

Please choose the appropriate answer.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
Research & Development	○	○	○	○	○	○	○	○
Forecasting & Scheduling	○	○	○	○	○	○	○	○
Production	○	○	○	○	○	○	○	○
Assembly	○	○	○	○	○	○	○	○
Quality assurance & management	○	○	○	○	○	○	○	○
Intra-logistics	○	○	○	○	○	○	○	○
External logistics	○	○	○	○	○	○	○	○
Maintenance	○	○	○	○	○	○	○	○
Service	○	○	○	○	○	○	○	○

What kind of systems does #c_0001# use for data processing?

Please choose one or more options from the list.

	Local implementation	Global implementation across sites
Own developments	☐	☐
ERP System (Enterprise Resource Planning) (e.g. SAP)	☐	☐
MES System (Manufacturing Execution System)	☐	☐
PLM System (Product Lifecycle Management)	☐	☐
CRM System (Customer Relationship Management)	☐	☐
Statistical Software (e.g. Minitab, R, SPSS, JMP)	☐	☐
Business Intelligence Software (e.g. SAS, QlikView)	☐	☐
Office without special add-ons (e.g. Excel)	☐	☐
Office with add-ons (such as SigmaXL)	☐	☐
Data mining (e.g. Rapid Miner (Rapid I))	☐	☐
Other (please specify):	☐	☐

To what extent are data analytics based decisions automated at #c_0001#?

Please indicate the degree of automated manufacturing data processing. If you do not have the exact value, please give your best estimate.

- ○ 1 (purely human-based decisions)
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6
- ○ 7 (self-optimizing machines, Artificial Intelligence)
- ○ I don't know

What kind of the following data types are currently used by #c_0001#?

We distinguish between active (e.g. product tells machine what to do) and passive (e.g. product collects information about its transport history). Please choose one or more options from the list.

	Currently in use	Planned use in the future	Not relevant
Active production data (e.g. product tells robot what to do with it)	☐	☐	☐
Passive production data (e.g. product memorises the ID of a component attached to it)	☐	☐	☐
Active logistics data (e.g. product tells packaging machine how to wrap it)	☐	☐	☐
Passive logistics data (e.g. product memorises details about the distribution cold chain)	☐	☐	☐
Active application data (e.g. product tells operator how to be handled)	☐	☐	☐
Passive application data (e.g. for guarantee claims the product memorises how it was treated)	☐	☐	☐

Which of the following five lean principles are supported due to the use of Big Data analytics at #c_0001#?

Please choose the appropriate answer. You can find an explanation here.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
Define value from the customer perspective	○	○	○	○	○	○	○	○
Identify the value stream	○	○	○	○	○	○	○	○
Implement the flow principle	○	○	○	○	○	○	○	○
Introduce the pull principle	○	○	○	○	○	○	○	○
Strive for perfection	○	○	○	○	○	○	○	○

Which of the following tasks is performed by #c_0001#'s Manufacturing Execution System (MES) and what do you think is essential for digitalization activities?

Please choose one or more from the following options.

	In use at #c_0001#	Essential to exploit benefits of digitalization activities
Detailed scheduling and process control	☐	☐
Equipment management	☐	☐
Materials management	☐	☐
Human resources management	☐	☐
Data acquisition	☐	☐
Performance analysis	☐	☐
Quality management	☐	☐
Information management	☐	☐
Energy management	☐	☐
Order management	☐	☐

In which of the following areas does #c_0001# make use of Blockchain technology?

Please choose the appropriate answer.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
Research & Development	○	○	○	○	○	○	○	○
Forecasting & Scheduling	○	○	○	○	○	○	○	○
Production	○	○	○	○	○	○	○	○
Assembly	○	○	○	○	○	○	○	○
Quality assurance & management	○	○	○	○	○	○	○	○
Intra-logistics	○	○	○	○	○	○	○	○
External logistics	○	○	○	○	○	○	○	○
Maintenance	○	○	○	○	○	○	○	○
Service	○	○	○	○	○	○	○	○

For which of the following applications does #c_0001# use Blockchain technology?

Please choose one or more from the following.

☐ Digital Identity ☐ Smart Contracts ☐ Digital assets ☐ Distributed apps

In which of the following areas does #c_0001# make use of Augmented Reality solutions?

Please choose the appropriate answer.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
Research & Development	○	○	○	○	○	○	○	○
Forecasting & Scheduling	○	○	○	○	○	○	○	○
Production	○	○	○	○	○	○	○	○
Assembly	○	○	○	○	○	○	○	○
Quality assurance & management	○	○	○	○	○	○	○	○
Intra-logistics	○	○	○	○	○	○	○	○
External logistics	○	○	○	○	○	○	○	○
Maintenance	○	○	○	○	○	○	○	○
Service	○	○	○	○	○	○	○	○

Does #c_0001# use Augmented Reality solutions to collaborate across locations within its (manufacturing) network (e.g. for training, problem solving)?

Please choose one option.

○ No

○ Yes

Which of the following five lean principles are supported due to the use of Augmented Reality solutions at #c_0001#?

Please choose the appropriate answer. You can find an explanation here.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
Define value from the customer perspective	○	○	○	○	○	○	○	○
Identify the value stream	○	○	○	○	○	○	○	○
Implement the flow principle	○	○	○	○	○	○	○	○
Introduce the pull principle	○	○	○	○	○	○	○	○
Strive for perfection	○	○	○	○	○	○	○	○

In which of the following areas does #c_0001# invest in Machine Learning?

Please choose the appropriate answer.

Definition of machine learning: An artificial system learns from examples and can generalize these after completion of the learning phase. This means that the examples are not simply memorized, but the system "recognize" patterns and regularities in the data.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
Research & Development	○	○	○	○	○	○	○	○
Forecasting & Scheduling	○	○	○	○	○	○	○	○
Production	○	○	○	○	○	○	○	○
Assembly	○	○	○	○	○	○	○	○
Quality assurance & management	○	○	○	○	○	○	○	○
Intra-logistics	○	○	○	○	○	○	○	○
External logistics	○	○	○	○	○	○	○	○
Maintenance	○	○	○	○	○	○	○	○
Service	○	○	○	○	○	○	○	○

What effects on the following factors has #c_0001# noticed due to the use of Robotics?

Please choose the appropriate answer.

	Significantly decreasing	Decreasing	Slightly decreasing	No changes	Slightly increasing	Increasing	Significantly increasing	I don't know
Direct production cost	○	○	○	○	○	○	○	○
Indirect production cost (overhead)	○	○	○	○	○	○	○	○
Product quality	○	○	○	○	○	○	○	○
Process quality	○	○	○	○	○	○	○	○
Delivery speed and quality	○	○	○	○	○	○	○	○
Flexibility (design)	○	○	○	○	○	○	○	○
Flexibility (volume)	○	○	○	○	○	○	○	○
Complexity of processes	○	○	○	○	○	○	○	○
Number of employees in production	○	○	○	○	○	○	○	○

5 Strategy

*Introduction >> Organization >> Technology >> **Strategy** >> Stakeholder >> Investments & Performance >> End*

What is the purpose of #c_0001#'s current Industry 4.0 or digitalization activities?

Please choose the appropriate answer.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
Increase production efficiency	○	○	○	○	○	○	○	○
Keep production in high-wage countries	○	○	○	○	○	○	○	○
Establishing new production sites in high-wage countries	○	○	○	○	○	○	○	○
Opportunity to offer new, digital products	○	○	○	○	○	○	○	○
Opportunity to offer new, digital services	○	○	○	○	○	○	○	○
Better implementation of existing business model	○	○	○	○	○	○	○	○
Creation of a new business model	○	○	○	○	○	○	○	○

How does #c_0001# approach the topic digitalization?

Please choose one option.

○ Strategic approach (long-term planning)

○ Explorative (trial-and-error principle)

○ Both

○ I don't know

How does #c_0001# push digitalization internally?

Please pick the most dominant alternative.

○ *No specified approach*

○ Top-down: Integrated concept from top-management (masterplan to organise all digitalization activities)

○ Bottom-up: Single projects / initiatives initiated by shop-floor employees

○ Both, combination of top-down & bottom-up

○ I don't know

How does #c_0001# develop digitalization solutions?

Please pick the most dominant alternative.

○ Each site develops its own ideas and solutions.

○ Competence Centers develop digitalization solutions and distribute them to other locations.

○ One site (lead factory) develops all digitalization solutions and provides them to other company sites.

○ One site develops digitalization solutions, but in addition each site can work on solutions individually.

○ Only external partners develop digitalization solutions for us.

○ I don't know

How has #c_0001#'s short- and long-term planning of production changed through the use of digital technologies?

Please indicate the change of the planning horizon with the help of the sliders.

Short-term planning

Long-term planning

Where does #c_0001#'s data for forecasting and scheduling come from?

Please indicate whether you process real-time, near-time or historical data.

	Historical data (month to years)	Near-time data (hours to days)	Real-time data (seconds to minutes)
Market data	☐	☐	☐
Economic data	☐	☐	☐
Supplier data	☐	☐	☐
Customer data	☐	☐	☐
Machine data	☐	☐	☐
Warehouse data	☐	☐	☐
Quality data	☐	☐	☐

What are barriers for #c_0001# regarding the successful application of digital technologies and which of them have you already overcome?

Please choose one or more options from the list.

	Barrier?	Already overcome
Budget restrictions	☐	☐
Resistance of the employees	☐	☐
Lack of capabilities and knowledge	☐	☐
Courage of leadership	☐	☐
Organizational Silos	☐	☐
Missing use-cases	☐	☐
Transferability (successful use cases cannot be generalized)	☐	☐
Existing infrastructure restrictions	☐	☐
Technical feasibility	☐	☐
Data volume	☐	☐
Data quality	☐	☐
Data protection / IT security	☐	☐
Missing norms and standards	☐	☐

6 Stakeholder

*Introduction >> Organization >> Technology >> Strategy >> **Stakeholder** >> Investments & Performance >> End*

How do the following stakeholder(s) contribute to #c_0001#'s digitalization activities?

Please choose one or more from the following options.

	No collaboration	Provide us with information	Prototyping / Mock-up	Commissioned Research	Joint Research	Provide complete solutions
Suppliers	☐	☐	☐	☐	☐	☐
Customers (user)	☐	☐	☐	☐	☐	☐
Customers (distribution partner)	☐	☐	☐	☐	☐	☐
Competitor	☐	☐	☐	☐	☐	☐
Provider	☐	☐	☐	☐	☐	☐
Consultancy	☐	☐	☐	☐	☐	☐
Research institution / Universities	☐	☐	☐	☐	☐	☐
External start-up companies	☐	☐	☐	☐	☐	☐
Associations	☐	☐	☐	☐	☐	☐
Unions / Works council	☐	☐	☐	☐	☐	☐

How does #c_0001# motivate its customers and suppliers to exchange data?

Please choose one or more from the following options.

	Suppliers	Customers (user)	Customers (distribution partner)
Voluntary basis	☐	☐	☐
Bilateral access to the data	☐	☐	☐
Discount on products	☐	☐	☐
Rewards or bonus program	☐	☐	☐
Data is collected automatically (no choice for stakeholders)	☐	☐	☐

How does #c_0001# ensure that its employees can use digital technologies in manufacturing?

Please choose one or more from the following options.

- ☐ "Training on the job"
- ☐ Verbal instruction
- ☐ Online seminars
- ☐ Manuals
- ☐ Internal wiki
- ☐ Training and workshops
- ☐ Introduction videos
- ☐ New training programs
- ☐ Simple, intuitive user interfaces
- ☐ Others (please specify): ____

Does #c_0001# offer platform(s) for data exchange with its external partners?

Please choose one option.

- ○ No
- ○ Yes, various single applications *connected* to one data base.
- ○ Yes, varioussingle applications *not connected* to one data base.
- ○ Yes, integrated platform(s) containing several apps.
- ○ I don't know

How would you evaluate the satisfaction of the following stakeholders regarding #c_0001#'s digitalization activities?

Please give your best estimate.

	Very dissatisfied	Dissatisfied	Relative dissatisfied	Neither satisfied nor dissatisfied	Relative satisfied	Satisfied	Very satisfied	I don't know
Supplier satisfaction	○	○	○	○	○	○	○	○
Employee satisfaction	○	○	○	○	○	○	○	○
Customer (user) satisfaction	○	○	○	○	○	○	○	○
Customer (distribution partner) satisfaction	○	○	○	○	○	○	○	○
Union / Work council satisfaction	○	○	○	○	○	○	○	○

7 Investments & Performance

*Introduction >> Organization >> Technology >> Strategy >> Stakeholder >> **Investments & Performance** >> End*

What share of #c_0001#'s revenue was invested in digital technologies during the last year?

Please state rounded percentages. In case that you do not know the exact share, please give a realistic assumption.

[ ] %

What are the effects of digitalization on the following factors at #c_0001#?

Please choose the appropriate answer.

	Significantly decreasing	Decreasing	Slightly decreasing	No changes	Slightly increasing	Increasing	Significantly increasing	I don't know
Direct production cost	○	○	○	○	○	○	○	○
Indirect production cost (overhead)	○	○	○	○	○	○	○	○
Product quality	○	○	○	○	○	○	○	○
Process quality	○	○	○	○	○	○	○	○
Delivery speed	○	○	○	○	○	○	○	○
Delivery reliability	○	○	○	○	○	○	○	○
Flexibility (volume)	○	○	○	○	○	○	○	○
Number of employees in manufacturing	○	○	○	○	○	○	○	○
Work safety	○	○	○	○	○	○	○	○
Stock levels	○	○	○	○	○	○	○	○
Complexity of processes	○	○	○	○	○	○	○	○
Speed of time-to-market	○	○	○	○	○	○	○	○
Pressure on sites in high-wage countries	○	○	○	○	○	○	○	○
Pressure on sites in low-wage countries	○	○	○	○	○	○	○	○

What is the maximal return-on-investment (ROI) duration for new, digital technologies in order to be acceptable for #c_0001#?

Please choose one option.

○ < 1 year

○ >1 - 2 years

○ >2 - 5 years

○ >5 - 10 years

○ >10 years

○ No restriction

○ I don't know

Which of the following statements describe #c_0001#'s changes since implementing digital technologies in manufacturing?

Please choose the appropriate answer.

	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree	I don't know
More products are produced with less/the same **direct labour hours**.	○	○	○	○	○	○	○	○
More products are produced with less/the same **indirect labour hours (overhead)**.	○	○	○	○	○	○	○	○
More products are produced with less/the same **machine hours**.	○	○	○	○	○	○	○	○
More products are produced with less/the same **raw materials**.	○	○	○	○	○	○	○	○
More products are produced with less/the same **energy consumption**.	○	○	○	○	○	○	○	○
*We use new/additional KPIs to measure the **success of digitalization** activities.*	○	○	○	○	○	○	○	○

How do you evaluate #c_0001#'s digital maturity compared to the one of its competitors?

Please choose one option.

- I don't know
- Follower
- Below industry average level
- On industry average level
- Above industry average level
- Pioneer

How has the performance of #c_0001# changed in comparison to the one of its competitors during the last three years?

Please indicate the development for the following factors.

	Much worse	Worse	Slightly worse	No change	Slightly better	Better	Much better	I don't know
Turnover	○	○	○	○	○	○	○	○
EBIT	○	○	○	○	○	○	○	○
Market share	○	○	○	○	○	○	○	○
Manufacturing/Operations costs	○	○	○	○	○	○	○	○
Product quality	○	○	○	○	○	○	○	○
Delivery speed and reliability (on-time)	○	○	○	○	○	○	○	○
Flexibility (design)	○	○	○	○	○	○	○	○
Flexibility (volume)	○	○	○	○	○	○	○	○
Innovative ability (product)	○	○	○	○	○	○	○	○
Image / brand recognition	○	○	○	○	○	○	○	○
Services (e.g. After-Sales Service)	○	○	○	○	○	○	○	○
Sustainability	○	○	○	○	○	○	○	○

8 Ende

Introduction >> Organization >> Technology >> Strategy >> Stakeholder >> Investments & Performance >> End

What do you think about digitalization of manufacturing processes? How can new technologies support high-wage manufacturing locations?

When you think of the most successful companies dealing with digital technologies, which companies come to your mind?

Mentioned companies might be within your industry or even in completely different industries.

	Company name	Reason
1st		
2nd		
3rd		

Thank you very much for your valuable contribution and the participation in our benchmarking!

Click on "Continue" to finish this survey. Afterwards, the results cannot be changed anymore.

9 Endseite

Thank you for your participation - You have finished this survey!

We look forward to provide the results as soon as possible. Please do not hesitate to contact us for further information on this or other projects of the Institute of Technology Management at the University of St.Gallen.

Appendix J: Semi-structured interview guideline

Christoph Benninghaus
Interview Guideline

Institut für Technologiemanagement
Universität St.Gallen

Impact of Digitalization
On the Strategic Management of International Manufacturing Networks

0. Introduction

- Introduction of the interview partners
- Short presentation of the research topic
- General information
  - *Objectives, process and schedule of the interview*
  - *Introduction of content and topics of the interview*
  - *Evaluation procedure (incl. confidentiality, anonymization)*
- Opportunity for further questions

Notes

1. Digitalization activities

Digitalization from the internal perspective: Use of (digital) technologies to improve internal processes and efficiency in different departments and plants of a company.

a) *How important is the use of digital technologies for your company?*
b) *What were the milestones since your company pushed digitalization?*
c) *What digital technologies does your company apply? Which offer the greatest potential?*
d) *What is the planned technology portfolio?*
e) *On which technologies will your company focus in the future?*
f) *Which technologies have the greatest potential for changing the roles and tasks of sites (and the manufacturing network)?*

Notes

1 | 3

Christoph Benninghaus
Interview Guideline

Institut für Technologiemanagement
Universität St.Gallen

2. Strategy

a) *What is the purpose of your digitalization activities (e.g. strengthening production in the home country, relocation, increasing efficiency, new business models, etc.)?*
b) *How has your organization mainly anchored digitalization activities organizationally and how does it plan to adapt them (e.g. centralized, decentralized, functional, CoE, project team, lead factory)?*
c) *How would you rate the degree of connectivity and automation in your plants? What are differences worldwide?*
d) *At which sites does your company automate increasingly? Why?*
e) *How important is cooperation with external stakeholders for you in the context of digitalization? What are differences worldwide?*

Notes

3. Site roles

a) *How many sites does your company operate and where are they located?*
b) *What are the most important location factors for your plants (e.g. costs, taxes, political stability, qualified employees, customer proximity)?*
c) *Who is responsible for digitalization in the manufacturing network?*
d) *Have you defined plant roles? If yes, what are the roles and how are they managed?*
e) *Have you defined a lead factory? If yes, for what (e.g. product, region)?*
f) *What are responsibilities or tasks of single plants and especially of the lead factory?*
g) *What are new responsibilities and tasks of the lead factory in the context of digitalization?*

Notes

4. Network configuration

a) To what extent do your production locations differ in the use of technologies?
b) How have tasks and responsibilities changed due to the implementation of digital technologies (e.g. new product allocations)?

c) *How are smart and collaborative robotics changing the production network?*
d) *Are you using IT solutions (e.g. MES) or augmented reality (AR) solutions across sites? How has the coordination and cooperation of the locations changed?*
e) *How does your company transfer technologies within the manufacturing network?*
f) *How important is the infrastructure at the sites for digitalization activities? Where do you see differences worldwide?*

Notes

5. High-wage location(s)

a) *How integrated are your high-wage locations in the network?*
b) *What are typical tasks of the high-wage location with regard to digitalization?*
c) *What competencies are necessary in this context (e.g. resources, know-how)?*
d) *What opportunities and risks does digitalization offer for labor-intensive locations?*
e) *What is the future perspective for your high-wage location(s)? Why?*
f) *Which strategy is more suitable for the high-wage location(s): "technological leader" or "follower"? What are the advantages and disadvantages from your perspective?*
g) *Optional: Why did your company build a new factory in a high-wage location? What were the main reasons and decision criteria? What is the level of automation of the new site? How large are the investments? What are the new role and responsibilities of this factory? Why did your company chose this location and what are advantages in contrast to other (possible high-wage or low-wage) locations worldwide?*

Notes

6. Finishing the interview

- Thank you for the interesting conversation
- Brief indication of how and when the information respectively results of the interview will be shared or published (i.e. dissertation)
- Further questions from the interview partner

Appendix K: Technology transfer

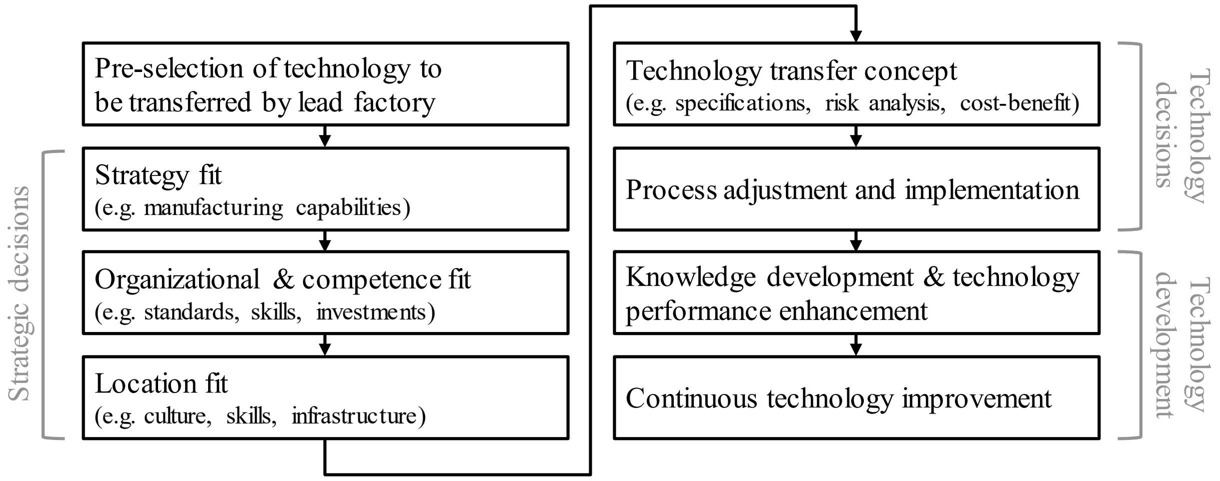

Figure 26: Technology transfer from lead factory to other sites (own illustration)

Appendix L: Extended evolutionary path of plants

The broken lines have been identified and discussed by Ferdows (1997b).

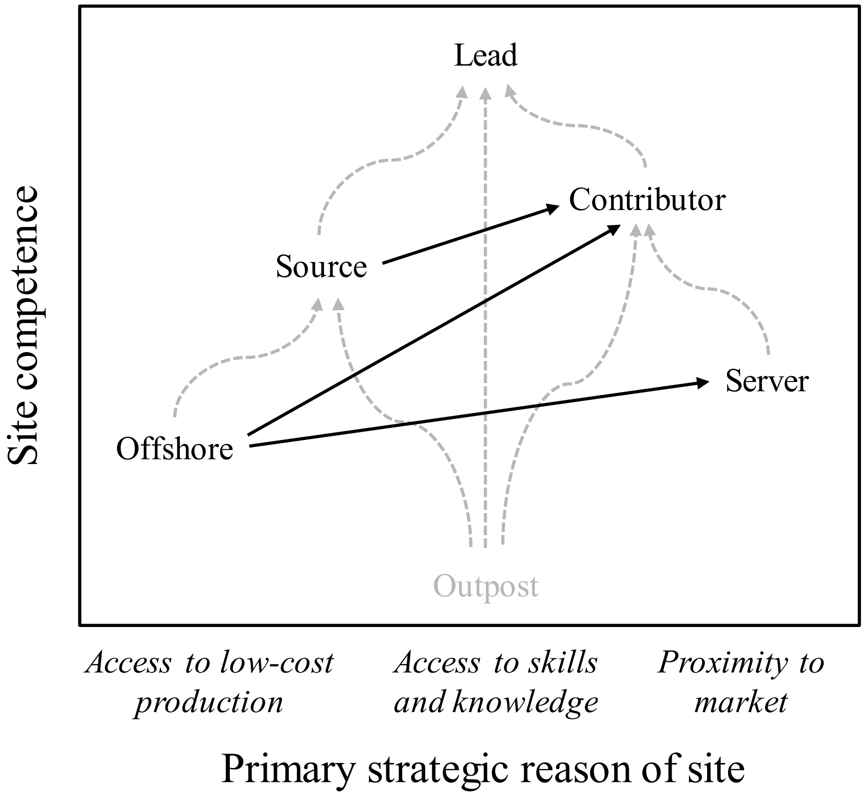

Figure 27: Extended plant evolution based on Ferdows (1997b) (own illustration)

Curriculum Vitae

Personal Data

Name	Christoph Benninghaus
Date of birth	15.08.1987
Place of birth	Düsseldorf, Germany
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Education

2015 – 2018	University of St.Gallen, St. Gallen, Switzerland *Doctoral studies in Business Innovation*
2011 – 2014	RWTH Aachen University, Aachen, Germany *Studies in business administration and engineering (M.Sc.)*
2012 – 2013	Tsinghua University, Beijing, China *Studies in management science and engineering (M.Sc.)*
2007 – 2011	RWTH Aachen University, Aachen, Germany *Studies in business administration and engineering (B.Sc.)*
1998 – 2007	Annette-von-Droste-Hülshoff Gymnasium, Düsseldorf, Germany *Abitur (German A-Level equivalent)*

Professional Experience

2018 – …	Hilti AG, Schaan, Liechtenstein *Program manager Industry 4.0* *(department: global manufacturing strategy)*
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