Chapter 1
Integrative Production Technology—Theory and Applications

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1.1 Global Economic Background

Production technology comprises the machinery, tools, infrastructure and know-how to make physical products. Therefore, production technology is the foundation of the manufacturing sector, including a vast range "from small-scale enterprises using traditional production techniques [...] to very large enterprises sitting atop a high and broad pyramid of parts and components suppliers collectively manufacturing complex products such as aircrafts" (Eurostat 2015a). For the different subsections of manufacturing, the reader may refer to the ISIC classification scheme (United Nations 2008).

Globally, the manufacturing share of the Gross World Product (GWP) is approximately 15 %, which amounts to nearly US$12 trillion (World Bank 2016a). Considering the value added in manufacturing from 1980 to 2015 of leading

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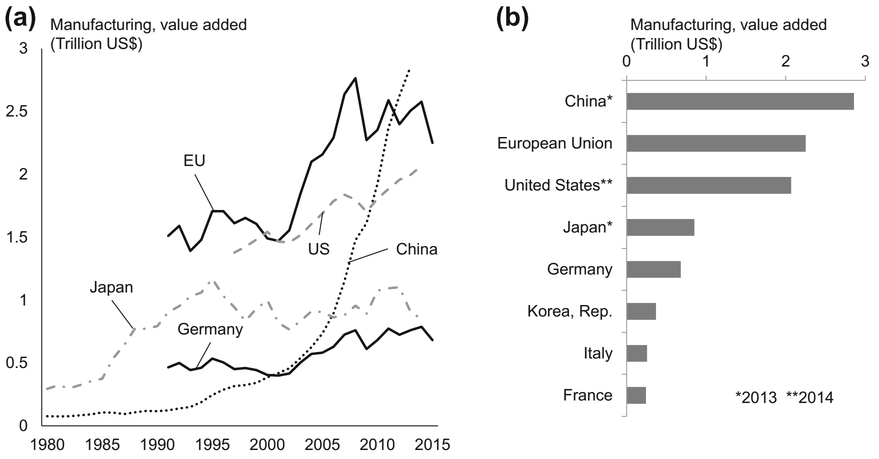

Fig. 1.1 Value added in manufacturing (US$) based on data by the World Bank (2016a). **a** Development from 1980 to 2015. **b** Ranking of countries and the EU with respect to value added in manufacturing based on data from the year 2015

countries, China's trajectory sticks out (see Fig. 1.1a). With an average growth of almost 15 % p.a., China overtook the USA as the world's largest manufacturer in 2010. Today, the combined manufacturing Gross Domestic Product (GDP) of Japan, Germany, Korea, Italy and France is lower than that of China (see Fig. 1.1b).

The share of manufacturing in the GDP is diverse across Europe and the world (see Fig. 1.2). Further, there is no clear correlation between the wealth of a country and the share of manufacturing sector. Globally, the share of manufacturing in the GWP fell almost monotonously from 21 % in 1995 to 14 % in 2014. In particular, many rich countries have experienced a relative decline of the manufacturing sector. Prominent examples for this decline are the USA and the UK. For these, the share of manufacturing in GDP fell from 17 to 13 % and from 18 to 11 %, respectively, in only 10 years from 1997 to 2007, and stayed at that level since. In contrast, the respective share has been almost constant in Germany and China during this time.

The importance of manufacturing for an economy is difficult to measure. Its share in GDP and GWP is only one indicator of many. While this share is relatively small (15 % of GWP), manufacturing contributes 71 % to global merchandise exports (World Bank 2016a). In manufacturing-oriented economies like China or Germany, this share is as high as 94 and 83 %, respectively (see Fig. 1.3a). Considering highly industrialized countries such as Germany, the range of exported manufactures is wide (see Fig. 1.3b), requiring a broad range of technological know-how and a complex value network of people and organizations. Hidalgo and Hausmann (2009) introduced the Economic Complexity Index (ECI) as a measure of the product mix that countries are able to make. The index increases with number of products that a country produces. Table 1.1 shows that the ranking is led by highly industrialized countries with a relatively large share of GDP in

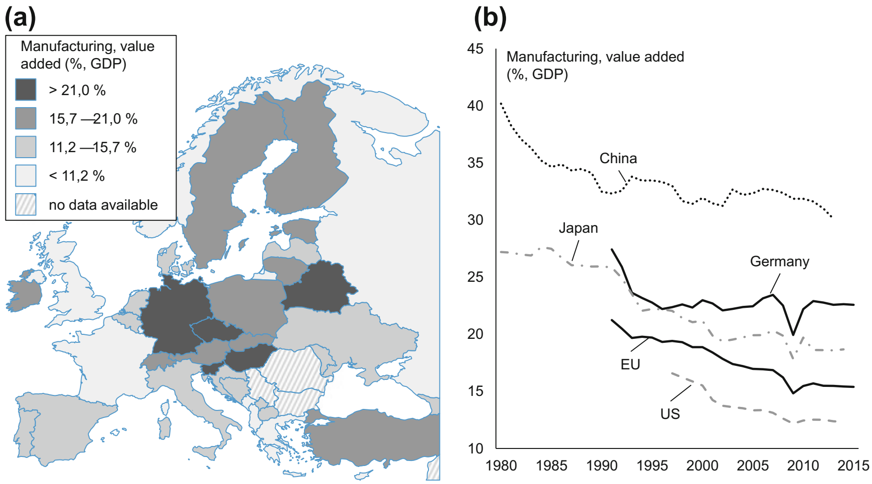

Fig. 1.2 Share of manufacturing in GDP based on data by the World Bank (2016a). **a** Situation in Europe in the year 2014. **b** Development from 1980 to 2015

manufacturing. Analogously to the ECI, the Product Complexity Index (PCI) is calculated from the number of countries that are able to make a certain product. Products like movements of watches, optical devices and gear-cutting machines lead this ranking. Countries that are able to make a complex product range (i.e., with high ECI) not only have higher general incomes, but also higher future economic growth rates (Hidalgo and Hausmann 2009). Therefore, countries with a large manufacturing base are generally better at handling economic crises, as has been observed after 2009.

The ability to make a wide and complex product range requires not only the right people and infrastructure, but also a continuous investment in Research and Development (R&D). Therefore, there is a high correlation between ECI and R&D expenditure. Countries with a high ECI and a large manufacturing base typically devote more than 2.5 % of their GDP to R&D (see Fig. 1.4). Generally speaking, a large part of the R&D expenditure belongs to the manufacturing sector. In Germany, for example, manufacturing accounts for 86 % of R&D spending (see Fig. 1.5a). Motor vehicles, computers, electronics, optical products as well as machinery and equipment are the main areas of R&D in the manufacturing sector (see Fig. 1.5b). Considering R&D spending as a rough metric for innovation, we can draw the conclusion that the share of manufacturing to a country's innovation rate is far greater than what the contribution of manufacturing to GDP might suggest (cf. Manyika et al. 2012). Therefore, the manufacturing sector is of great importance for a country's innovation capacity. Further, innovation in manufacturing is often the basis for new or more efficient services, such as in civil aviation.

The subsector of machinery and equipment has a special role within manufacturing. Comprising "machinery and equipment that act independently on materials

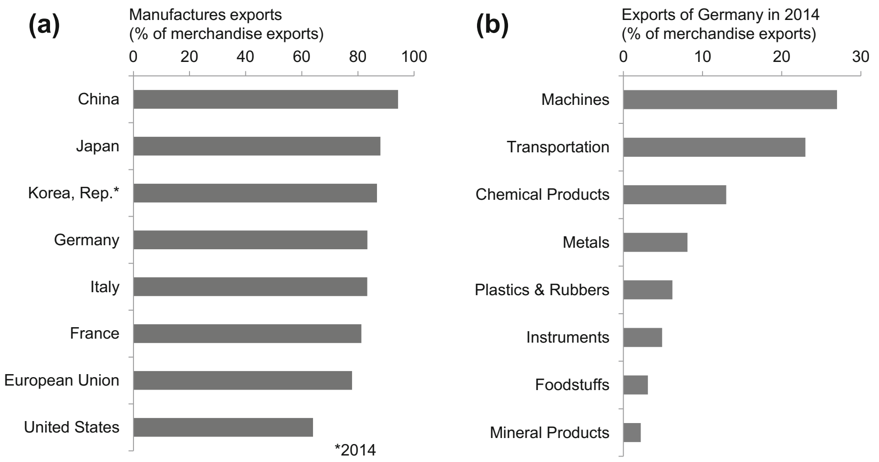

Fig. 1.3 Export data. **a** Share of manufactures in merchandise exports of leading manufacturing countries for the year 2015 based on data from the World Bank (2016a). **b** Shares of Germany's exports for 2014 based on data from (Simoes and Hidalgo 2016)

Table 1.1 Ranking with respect to the economic complexity index (Simoes and Hidalgo 2016)

Rank	Country	ECI
1	Japan	2.25
2	Switzerland	2.10
3	Germany	2.05
4	Sweden	1.89
5	USA	1.80

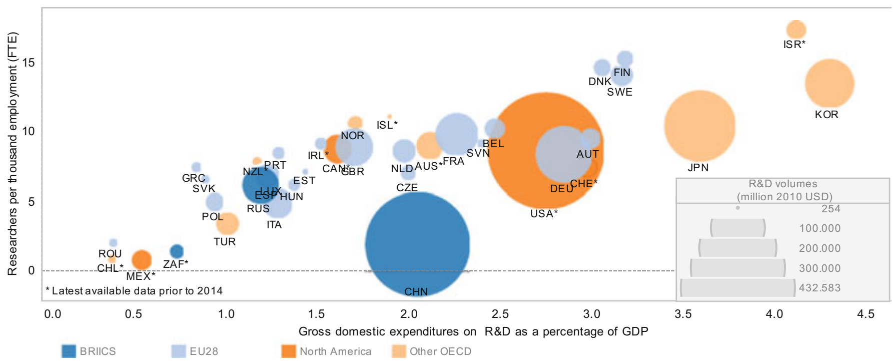

Fig. 1.4 Human and financial resources devoted to R&D (2014). The figure is adapted from the OECD (2016), an intergovernmental organization that includes mostly rich countries and has been visually edited by the authors

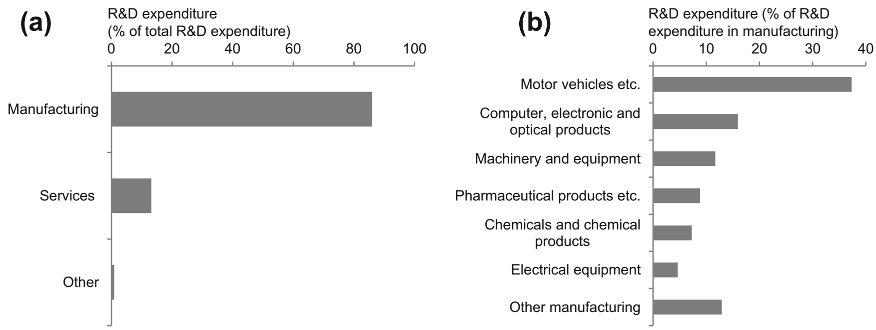

Fig. 1.5 Business enterprise R&D expenditure in Germany by industry sectors for 2013 (OECD 2016)

either mechanically or thermally or perform operations on materials" (United Nations 2008), the sector is business-to-business oriented, supplying the other subsectors of manufacturing with the facilities and technology for production. The subsector is therefore an enabler for whole areas of manufacturing. Moreover, in the case of Germany, machinery and equipment significantly contributes to exports (see Fig. 1.3b) and innovation. As of 2014, German manufacturers of machinery and equipment invested 5.6 % of their revenue in innovation activities, and the share of R&D employees continuously increased from 6.3 % in 2003 to 8.0 % in 2013 (VDMA 2016).

Due to its central role, many countries consider manufacturing in general and the subsector of machinery and equipment as key factors for economic success. Nevertheless, the impact on society is, of course, not only macroeconomic. Innovation-driven productivity gains are often passed on to consumers in the form of lower prices (Manyika et al. 2012). In general, the maturity of production technology makes the difference with regard to price between products that are suitable for a small fraction of a population and the wide share. Electric cars, OLEDs and fiber composites are widely discussed examples that are now in the transition toward mass applicability.

Manufacturing jobs are another big impact on society. In the period from 2005 to 2013, the number of manufacturing jobs in the EU declined by 10 %, while Germany's number rose by 1.8 %. During the same time, the relative share of manufacturing jobs with regard to total employment fell by 2 % in Europe and by 1 % in Germany (see Fig. 1.6). A report by McKinsey, a consultancy, predicts that the relative share of manufacturing employment in advanced economies will fall from 12 % in 2010 to below 10 % in 2030 (Manyika et al. 2012). The reasons are a proceeding productivity growth based on automation and process optimization as well as the low probability of a high demand increase. In contrast to common opinion, trade and offshoring have only a minor effect on jobs in advanced economies, as the McKinsey report and a study by Edwards and Lawrence (2013) indicate. However, while manufacturing employment typically declines in

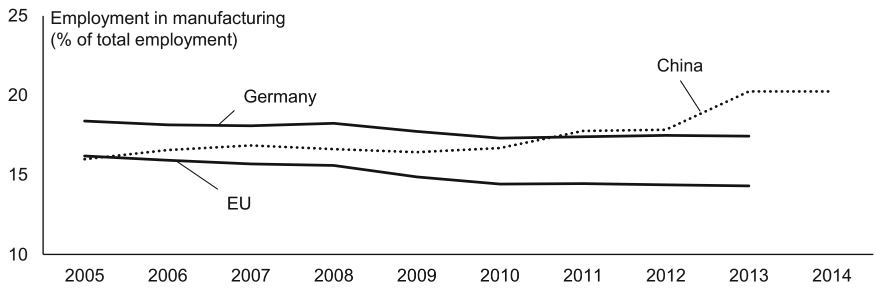

Fig. 1.6 Share of manufacturing employment based on data from (Eurostat 2015b) for the EU and Germany and on data from (NBS 2016) for China. [The share for China has been calculated considering urban units and urban private enterprises. The calculated numbers correspond to the results by Lardy (2015), who uses the same data from the National Bureau of Statistics of China NBS (2016). The inclusion of rural China—where approx. 50 % of Chinese are employed—will result in a lower share of manufacturing employment]

advanced economies, it still grows in emerging countries such as China. From 2005 to 2014, the number of urban manufacturing jobs in China increased from approximately 45 million to almost 80 million (NBS 2016). At the same time, the share of manufacturing in urban employment rose from 16 to 20 % (see Fig. 1.6).

The competitiveness of a certain region with regard to manufacturing is influenced by many factors. As a framework for location analysis, Manyika et al. (2012) consider innovation density, cost structure and tradability criteria for different product segments. The manufacture of basic metals, for example, is characterized by low R&D and labor intensity, lower-middle trade intensity and high capital as well as resource intensity. Medical devices, as another example, are easily tradeable, very R&D and capital intensive but relatively indifferent to energy and labor costs. Advanced economies with high-wages are typically competitive in sectors where success stems from regional proximity or is determined by innovation and quality, such as in cars, high-end electronics as well as machinery and equipment. However, emerging economies can also be leading with regard to production volume in innovative sectors such as machine tools (see Fig. 1.7). However, with

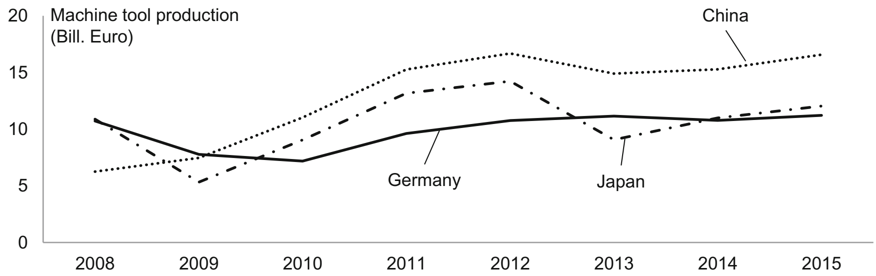

Fig. 1.7 World machine tool production of leading countries based on data from (VDW 2016) and earlier reports

respect to exports one will find the advanced economies like Germany and Japan in the top rankings. At the other end, easily tradeable goods with high labor intensity and low R&D efforts such as ordinary textiles are seldom manufactured in high-wage countries.

Resource consumption is not only crucial for the competitiveness in energy and raw material-intensive areas in manufacturing, but also impacts society in terms of environmental changes. In 2014, almost 70 exajoules have been consumed in the European Union, which results in an average of 3 kW per capita. Here, the share of industry is approx. 17 % in the EU and 19 % in Germany (see Fig. 1.8a). For Germany and most other industrial countries, the chemical industries as well as iron and steel production account for the largest part of industrial energy consumption (see Fig. 1.8b). For the case of Germany, the manufacture of machinery and transportation equipment together consumes 14 % of industrial energy, approximately equaling the domestic energy requirements for national and international aviation (Eurostat 2016b). Furthermore, the manufacturing sector is not only important with regard to potential energy savings in its own processes, but also indirectly contributes to energy and resource efficiency in transport, services and other sectors. Manufacturing innovations, for example, are necessary for efficient electric power generation and electromobility.

In conclusion, the analysis shows that manufacturing is still a key factor in a country's economic success in advanced economies—even though its share in the GDP has mostly declined during the last decades. Manufacturing contributes by far the largest part to exports in countries such as Germany, Japan, South Korea and China and is therefore essential for a positive trade balance. A country's ability to make a wide and complex range of products is also an indicator of its economic robustness. In global markets, high-wage countries can compete in segments that are determined by innovation, know-how and high skills. Therefore, countries such as Germany devote a large part of their R&D efforts to manufacturing. At the same time, manufacturing becomes increasingly high tech so that job profiles change from low to high skill, yielding higher labor productivity. Overall, the share of employment in manufacturing is likely to decrease further in future. However, the job market will still be significantly influenced by the success of the manufacturing

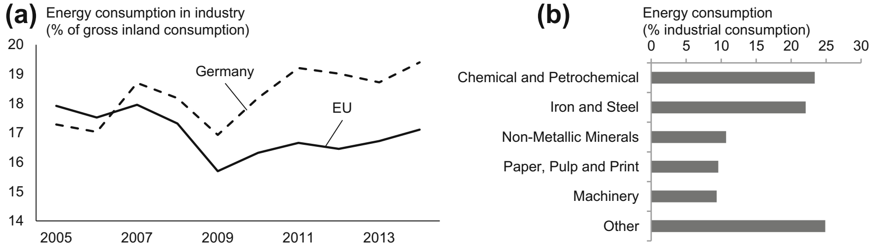

Fig. 1.8 Industrial energy consumption based on data from (Eurostat 2016b). **a** Industrial energy consumption in the EU and Germany from 2005 to 2014 as the share of total gross inland consumption. **b** Energy consumption in Germany for different industrial sectors as of 2014

sector, as manufacturing and service jobs often depend on each other and the line between the fields of activity is increasingly fuzzy. Beyond the societal importance, manufacturing has a significant impact on the environment: first, because of its share in emissions as well as energy and resource consumption; second, due to its influence on energy efficiency in other sectors such as transport; and third, because of its influence on waste in terms of recovering and recycling materials.

1.2 Opportunities and Challenges for Manufacturing Companies in High-Wage Countries

The depicted economic situation provides opportunities and challenges for manufacturers in advanced economies. This section outlines these challenges and their implications.

As high-wage countries are usually most competitive in markets where success stems from extensive know-how, quality and innovation, the supply of high-skilled workers and engineers is crucial. One key challenge is the demographic shift of many advanced economies. In the USA, for example, the median age of people employed in manufacturing is 44 years and almost one quarter of employees are older than 55 (BLS 2015). In the EU and Germany, approximately one fifth of the population are aged 65 and over (see Fig. 1.9), and this proportion is likely to rise further in the future. Manufacturing will need higher labor productivity to counteract the demographic shift. Moreover, the know-how of the people that soon will withdraw from employment must be replaced. Therefore, education and training are necessary that allow people from different cultural and academic backgrounds to contribute to manufacturing productivity. Support and knowledge management systems may additionally cushion the know-how drop. Nonetheless, it will not be sufficient to merely replace know-how, as manufacturing changes from low to high-skilled labor and the corresponding tasks from the physical to the digital world. Hence, current and future employees must be educated and trained for the ongoing industrial transformation.

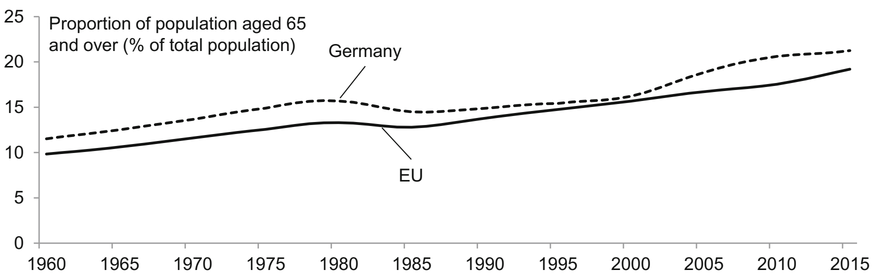

Fig. 1.9 Demographic shift in the EU and Germany based on data from (World Bank 2016b)

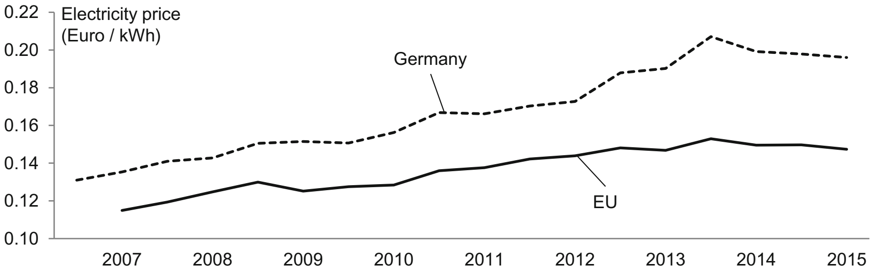

Fig. 1.10 Average electricity prices for industrial consumers with annual consumption between 500 and 2000 MWh including all taxes and levies (Eurostat 2016a)

Apart from skill shortages, many high-wage countries such as Germany and Japan import their raw materials and are confronted with volatile pricing. The global steel price index, for example, peaked at over 550 points in June 2008 and then fell back to approx. 150 points in November of the same year, a decrease of more than 70 % in just five month. Subsequently, the steel price doubled again during 2009. Similar volatility has been observed in the market for rare earth, where prices fell by 80 % in 2012 due to substitution, demand changes and new mining areas (WSJ 2015). In contrast, the price of electric energy almost increased monotonically for Germany and Europe, mainly because of taxes and levies (see Fig. 1.10). Considering increasing prices and volatility of commodities and energy, it is not only important to be resource efficient, but also to adapt product design and manufacturing processes to volatile prices, such as by material and process substitution or by making production plans more flexible to compensate short-term fluctuations in procurement prices.

At the customer side of the supply chain, manufacturing systems must quickly adapt to changing demand. Long-term sales forecasts and actual sales may differ significantly to consumer trends, substitution or global competition. Sales are, especially difficult to forecast in new markets such as electric cars. In 2015, for example, BMW sold 66 % more electric cars (i3 and i8) than in 2014 (Pankow 2016), an increase that could not have been predicted accurately. For manufacturing, this implies that those companies have a competitive advantage that can efficiently reconfigure and adapt their production systems for volatile demand. Beyond flexibility in production scale, a competitive advantage can be gained by fulfilling individual customer requirements at the cost of mass production, such as by variant configuration, customized engineering solutions and individualized production. Therefore, companies must be able to produce small batches down to batch size one, while keeping efforts for product change, run-in and programming low, for instance, by implementing intelligent automation and worker support systems.

Information and Communication Technology (ICT) is a key enabler for agility along the supply chain, making it possible to react flexibly to requests and changes at different nodes of the supply chain. To support and shape digital transformation,

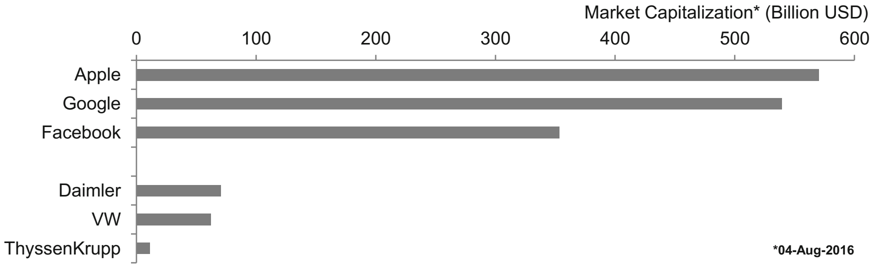

Fig. 1.11 Comparison of company market capitalization between US IT companies and German manufacturers based on data from (Reuters 2016)

most industrial countries have started initiatives such as *Industrie 4.0* in Germany, the *Industrial Internet Consortium* in the USA or the *10,000 Smart Factories Program* in South Korea. As Gausemeier and Klocke (2016) outline in an international benchmark, the transformation strategies differ by country. While Europe and especially Germany follow a strategy that is driven by engineering excellence and deep domain knowledge that should be refined by ICT, the US activities often start on the digital side and subsequently take innovations from Silicon Valley into the physical world. Big Data Analytics and Cloud Computing are examples of technologies that found their way from IT hotspots to industrial application. Due to their high market capitalization (see Fig. 1.11) and cash reserves, the US IT giants may be faster in entering the domain of manufacturing (cars, robotics, smart home, etc.) than the manufacturers becoming software or platform providers. However, manufacturers may have advantages in markets that require deep domain knowledge. Leveraging this domain knowledge in the context of modern ICT is also a key objective of the research that is presented in Chaps. 4, 8, 9 and 10.

China is currently on the leap to automation due to increasing wages and demographic change. Currently, the labor productivity in China is only 15–30 % of the OECD country average, as a recent study by McKinsey points out (Woetzel et al. 2016). If productivity is factored-in, China's labor costs are only 4 % cheaper than those of the USA (Yan 2016). The optimization of business processes by digitalization and the automation in factories are seen as great opportunities for productivity growth. The study points out that while China is the largest importer of robots, there are only 36 robots per 10,000 manufacturing workers, which is one tenth of the level in South Korea. Therefore, the five-year plan of 2016 includes the *Made in China 2025* strategy with the aim to build up an information-intensive infrastructure for manufacturing. Certainly, the sheer size of the manufacturing economy bears great potentials for industry and technology suppliers. Furthermore, automation solutions and data analytics will profit from scale effects as the wealth of a network increases disproportionally with the number of nodes. Today, China is

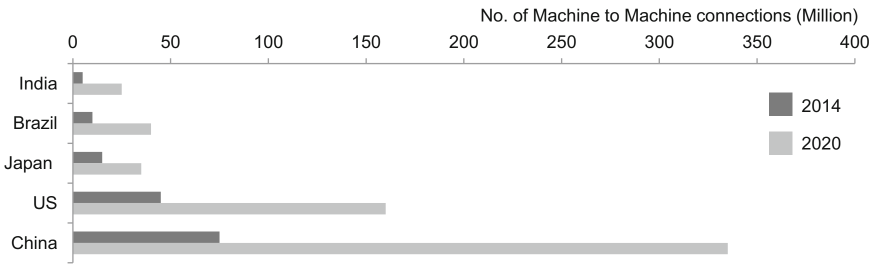

Fig. 1.12 Estimate of Machine-to-Machine (M2M) connections (GSMA 2015)

already the country with the most connected devices, and its lead will probably be even bigger in 2020 (see Fig. 1.12).

Alongside ICT, new or optimized manufacturing technologies allow companies to increase productivity, quality and flexibility while lowering costs. On the one hand, conventional technologies are continuously optimized. For instance, milling machines are equipped with fast and energy-efficient drives or plastics profile extrusion processes are virtually optimized (see Chap. 3). On the other hand, new methods and machine concepts are developed for additive or hybrid processes (see Chaps. 2, 6 and 7) that may reduce set-up times and shorten value chains. Furthermore, material properties such as weight and fatigue limits are still a decisive part to product added value, like in the transport or energy sector. Bringing new materials into production by understanding their behavior along the lifecycle is still a major challenge for industry. In this context, ICT advancements will facilitate the prediction and optimization of material-tailored production processes (see Chap. 5).

In conclusion, agility and innovation speed are the two key success factors for manufacturing in high-wage countries. Here, agility is the ability to adapt production systems to the dynamics of the commodities and customer markets. Innovation speed and time to market are decisive for the markets in which advanced economies typically compete and will become even more important as emerging economies transform from extended workbenches to innovators. As the times will shorten in which price top-ups can be gained through innovation, productivity growth remains an important objective for highly competitive markets. ICT is the key enabler for agility, innovation speed and productivity growth, and industrial companies will move toward digital enterprises as real and digital worlds merge. The applications are manifold, comprising the whole life cycle from design over prototyping and production to service. The digital transformation will certainly lead to new skill requirements. Therefore, education and training are the prerequisite for achieving agility and innovation in the future economy.

1.3 The Polylemma of Production[1]

As outlined in the preceding sections, high-wage countries are able to compete in markets that are driven by innovation, quality and individual customer requirements. However, to maintain their competitive advantage they need to offer products that match customer and societal demands at competitive prices on the one hand, while assuring optimized use of resources under market and societal changes on the other. Figure 1.13 shows that each of the two objectives is restricted by a dichotomy forming the polylemma of production: The market-oriented dichotomy addresses the tension between the manufacturing of products at mass production costs (economies of scale), while matching individual customer demands with a more diversified product range (economies of scope). The resource-oriented dichotomy is concerned with the balance between optimized use of production resources (planning orientation) and creation of value under high system dynamics (value orientation).

Economies of scale and low manufacturing costs can be achieved when products and processes are standardized and synchronized in such a way that increasing quantities leads to a reduction in the unit cost of the output. However, standardization and automatization decreases the potential degree of flexibility and versatility and therefore hinders the efficient production of individualized products and flexibility in case of change requests.

Increasing planning efforts and reliability means intensifying the use of models, simulations and optimization approaches in engineering and production processes, with the aim of improving the quality of the output. These steps primarily raise personnel expenditures and resources, but do not directly add value in terms of higher output or less waste.

Despite the dichotomous relationships, companies need to strive toward an ideal operating point within these tensions. Past and current trend is the relocation of production from high- to low-wage countries, mainly focusing on economies of scale and value orientation. In order to counter this trend and sufficiently increase profitability of production in high-wage countries, the resolution of the polylemma of production is essential toward finding the optimal balance on the scale scope axis and on the plan value axis.

In the Cluster of Excellence (CoE), a core hypothesis is that technological advances contribute to the resolution of both dichotomies (see Sect. 1.5 and Chap. 12).

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[1]This and the following chapters give a general overview on the vision and the research program of the Cluster of Excellence (CoE). Therefore, parts have already been published in other outlets of the CoE, for instance, on its website http://www.production-research.de.

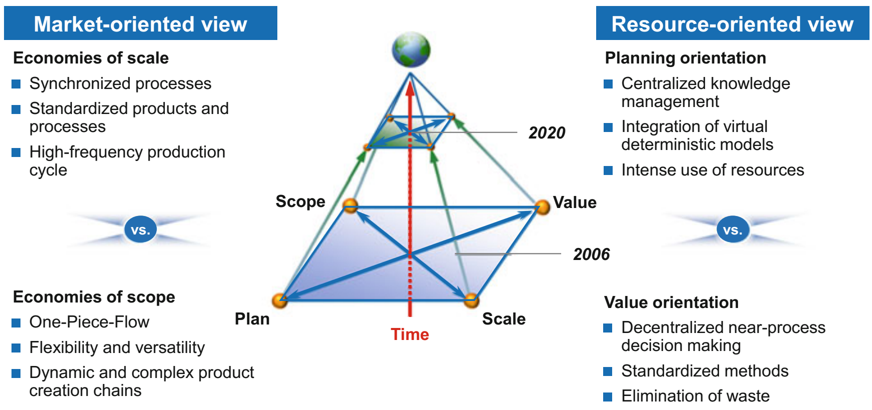

Fig. 1.13 Polylemma of production

1.4 Research Program

The vision of the CoE is to resolve the polylemma of production and thus contribute solutions to economically, ecologically and socially sustainable production in high-wage countries.

To accomplish this vision, a paradigm change is needed in the way production is researched today, opening up the scope of the CoE toward its challenging scientific objectives:

(i) to contribute coherent deterministic models for integrative product creation chains and harmonized cybernetic models of production systems to a holistic theory of production,
(ii) to advance and integrate key technologies for production in high-wage countries as well as,
(iii) to create a scientific workforce that can ideally cope with highly complex, dynamic and interdisciplinary scientific cooperation.

In order to research and implement this vision Aachen's leading scientists teamed up to form the Aachen House of Integrative Production.

The resolution of the dichotomy between scale and scope requires economically, ecologically and socially feasible approaches for increasingly Individualized Production (see Chaps. 2 and 3). Here, the goal is to realize one-piece-flow of individualized products at mass production costs from the two mutually exclusive perspectives of direct, mold-less and mold-based production systems.

A prerequisite for this integrative approach is a sound understanding of the interacting entities and domains of production such as humans, machinery, processes, materials and products. New ways for connecting these domains require integrated, harmonized and modular virtual modeling methodologies as well as tools for assessing and predicting product properties and production system capabilities.

Virtual Production Systems aim at the substantial improvement of prediction accuracy via semantic connectivity and enhancement of deterministic model chains, their application for inverse modeling and sensitivity analysis and the sustainable implementation into a modular, standardized platform (see Chaps. 4 and 5).

The technology and discipline-spanning comprehension and modeling of product creation chains enable systematic research on multi-technology integration. The combination of different materials and production processes leads to (i) disruptive innovation (e.g., processes, materials and products whose manufacture is impossible today) as well as to (ii) reduced resource consumption via shortened product creation chains. Thus, integrated technologies are a key research field with regard to the resolution of the polylemma and the future technological development of high-wage countries (see Chaps. 6 and 7).

As depicted, a major obstacle to resolving the polylemma is the shortcomings of current models and methods to cope with the unpredictability and complexity of production systems as a whole in their design as well as operation in a turbulent environment. Mechanisms of self-optimization are a key solution to these kinds of dynamic optimization problems that can be applied at different levels of production systems from the entire plant down to the level of machinery and single processes (see Chaps. 8, 9 and 10). The goal is to research and develop socio-technical production systems within a population network which are able to autonomously define, reach and maintain optimal operating points based on symbolic and sub-symbolic cybernetic models. This goal requires a significant increase in the system transparency that was achieved through the research results on object-to-object communication in the first funding period of the CoE.

To ensure personnel sustainability, Cross-Sectional Processes (CSP) comprise activities in the field of Scientific Cooperation Engineering (see Chap. 11). These address the issues of Knowledge and Cooperation Engineering, Interdisciplinary Innovation Management, Diversity Management and Performance Measurement. They provide the research work of the research projects with appropriate steering and support, following the vision that highly complex, dynamic and interdisciplinary science requires fundamental research on scientific education, the resolution of cultural understanding as well as high-resolution and networked knowledge management.

To ensure structural sustainability, the CoE pursues the establishment of technology platforms (see Chap. 13). They bundle and focus research results of the CoE on leading-edge key technologies and capabilities for high-wage country product creation chains. Within the platforms, well-developed topics and technologies of the CoE are prepared to structurally stand on their own within new entities and institutions at RWTH Aachen University.

1.5 Theory of Production

For increasing the competitiveness of production systems in high-wage countries, an integrative approach that unifies different aspects of production technology and that enables the optimal balance within the polylemma of production is essential. From a scientific point of view, this can be achieved by means of a common theory of production. With the aid of scientific laws, theorems and models, theory of production helps understand real-world scenarios and correlations by describing and predicting the dynamic behavior of complex production systems for increasing value creation. On the one hand, deterministic models and the quantification of predictable relationships within a production system reduce complexity (Complexity Reduction), while on the other cybernetic models can be developed and applied to control unpredictable scenarios (Complexity Control).

Existing production theories mainly focus on economic processes and relationships within a production system by describing transformation processes around goods (Chap. 12). For a holistic understanding, technical dependencies need to be additionally considered and analyzed. This opens up the opportunity to not only address cost factors, but also product and process-related factors such as flexibility of the product portfolio, product and service quality; and delivery performance in planning, forecasting and management of production that highly depend on the technologies and methods that are being applied.

Instead of regarding a manufacturing process as a black box, it is necessary to understand the influence of certain process parameter variations on the performance of superior production levels. In addition to direct processes on the shop floor, engineering efforts need to be examined and evaluated within a production theory, as these efforts can strongly influence the performance of a production system (Return on Engineering). Depending upon the development methods employed, for instance, time to market and development costs can vary and therefore impact profitability. For an integrative approach with the aim of finding the global optimum of a production system regarding time, cost and quality as well as the balance within the polylemma of production, a production theory should furthermore always address the whole value chain instead of single value stages.

Currently arising global trends and developments such as performance improvement of hardware and software, virtualization of networked physical systems, new product and process development methods, and higher service orientation provide a good basis to solve the polylemma of production. Modularization and iterative development methods such as scrum from computer science in combination with new manufacturing technologies like additive manufacturing improve the positioning on the scale scope axis, as such technologies enable the faster development of new and individualized products at lower costs (see Chap. 2). Virtually networked machines and humans allow a better communication and information exchange for high-quality planning and flexible production control thereby improving the balance between plan and value orientation (see Chap. 6).

The question is what technological and managerial approaches in detail contribute to the resolution of the polylemma of production? In response, the research carried out in the CoE serves as a foundation for the analysis of the impact of technological and managerial advances on the profitability of a production system. The examined technological use cases comprise both manufacturing technologies and indirect processes like material and prototype development. In the subchapters "Profitability Assessment as a Contribution to the Theory of Production" of the following chapters, the profitability drivers of these use cases are determined, and their profitability measures are qualitatively described. After the classification and evaluation of the existing production theories concerning the requirements presented above for an integrative production theory in Chap. 12, the profitability assessments of the diverse technologies and processes are compared and consolidated within a common framework to filter those results that strongly influence the profitability and the performance of the production system.

On the basis of this common framework, mathematical models are developed that describe the mutually influencing variables on a certain profitability driver. These variables consist of both technological and managerial factors. The integration of the models into a profitability metric is an attempt to develop a new integrative production theory that is able to improve the understanding of the interrelations between single sub-models of a production system. Moreover, this framework is intended to support decision makers to identify the optimal operating point within the polylemma of production with the aid of technological advances.

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