Chapter 12
Towards a Technology-Oriented Theory of Production

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Contents

12.1 Summary

Research in the field of production theory aims at describing the transformation processes around goods in the form of quantitative relationships between input and output values (Dyckhoff 2006). Production is treated as a black box, neglecting

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crucial technological impact variables. Furthermore, the area of analysis is generally restricted to transformation processes within direct areas of manufacturing systems. Finally, costs are considered as the only measure of success (Nyhuis and Wiendahl 2010).

The developed approach of our technology-oriented theory of production seeks overcoming these limitations in current production theory. Consequently, the following three goals have been established: First, the impact of current technological advances within cutting-edge research on manufacturing technologies on profitability is operationalized. Second, the area of analyzed transformation processes is extended from manufacturing to indirect processes like prototype development or production planning and control. Third, in addition to costs—three further performance factors are integrated as measures of success: product and service quality, delivery performance (e.g., by taking into account time to market) and flexibility of the product portfolio (e.g., by taking into account product variant commonalities). As these four measures of success are generally considered mutually exclusive (Boyer and Lewis 2002), it is necessary to take their dichotomous relationship into account when developing a metric for profitability. This is done by introducing the polylemma of production as the main conceptual framework in the developed theory.

The theory building process was conducted within the following four technological domains of the Cluster of Excellence 'Integrative Production for High-wage Countries': additive manufacturing, virtual production, self-optimized production and integrated technologies. All four domains were examined by a three-stage approach. In the first stage profitability drivers within all technological use cases of the cluster were identified and their impact on profitability measures described qualitatively. In the second stage all identified drivers were consolidated in order to filter those with a relevant impact on profitability. Finally, the identified profitability patterns were formalized with respect to their impact on the four performance factors.

The resulting profitability metric contributes new particular models to current production theory, enhancing it with its deeper understanding of the technological black box. Furthermore, decision-makers shall benefit due to a framework that helps them align strategic decisions within the four competitive priorities with corresponding investments in manufacturing technologies.

12.2 Research Motivation

Four operational capabilities are widely accepted as crucial factors which determine a manufacturing company's strategic direction and competitiveness: cost, quality, flexibility and delivery performance (Schmenner and Swink 1998; Ward et al. 1998).

Globalization and its accompanying rising market uncertainties are intensifying the pressure on manufacturing companies—especially in high-wage countries—to improve in all four competitive factors (Lanza et al. 2012). Due to low-wage levels

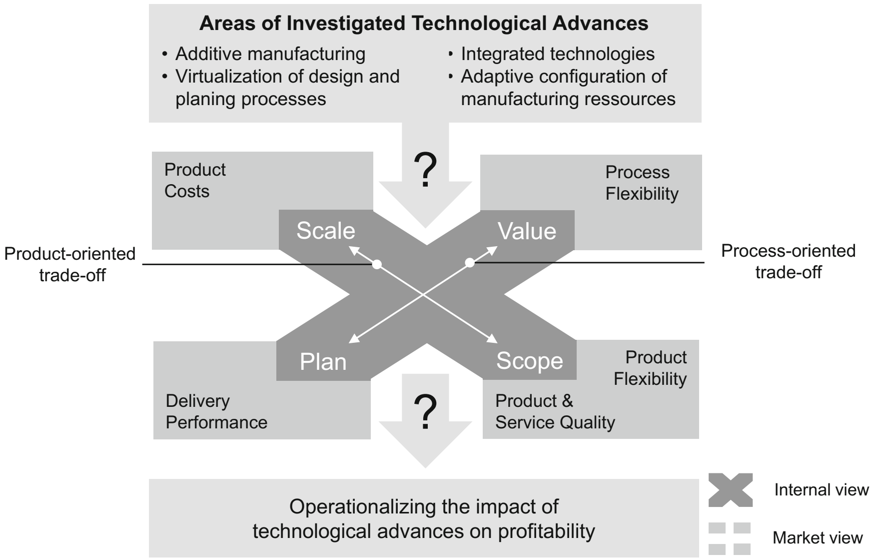

Fig. 12.1 Research framework of the technology-oriented theory of production

in developing countries, manufacturing companies are constantly forced to identify and realize rationalization potential within their direct and indirect processes for increasing internal economies of scale (Steinhilper 2012).

In contrast to cost leadership, diversification represents a second competitive strategy (Porter 1998). Instead of gaining customers by undercutting competitor's prices, diversification aims at increasing revenues by satisfying individual customer needs in terms of high product and service variety as well as quality. In order to do so, companies are forced to increase their internal scope of tools and other manufacturing resources. The involved increase in flexibility generally tends to counteract economies of scale that are based on high degrees of resource standardization. This opposing relationship between costs on the one hand and product flexibility and quality on the other constitutes the product-oriented trade-off within the four competitive priorities (see Fig. 12.1).

The opposing relationship between delivery performance and process flexibility constitutes the process-oriented trade-off within the competitive priorities. A main determinant of delivery performance is the calculability respectively planning reliability of a firm's development and order fulfillment processes (Schuh et al. 2014a). However, in the context of volatile market conditions and often-changing customer requirements, planning processes tie up a lot of resources in iterative planning loops. Such activities counteract the goal of highly flexible and responsive production processes that are especially needed in small batch production.

Figure 12.1 illustrates the dichotomous relationships between all four competitive priorities. Besides the distinction between a product and process-oriented trade-off, two further classifications are introduced: a market-oriented view and an internal-oriented view. The latter corresponds with the polylemma of production and links it to the four general competitive priorities (cost, quality, flexibility, delivery performance).

Several researchers argue that a simultaneous optimization of all four performance factors cannot be realized due to the described opposing relationships (Skinner 1974). Based on this point of view, a resulting recommended action for production management is to consequently focus mainly on one competitive factor at a time (Porter 1998). However, in contrast to this exclusive focus on one competitive priority, it is also argued that managerial and technological advances lower the dichotomous relationships between the competitive priorities allowing manufacturing companies to realize hybrid strategies (Skinner 1996; Jenner 2000). A systematic modularization of the product architecture can be mentioned as a managerial approach to limit complexity costs on the one hand and increase perceived product variety—and hence flexibility—on the other (Schuh et al. 2014a). Similarly, advanced manufacturing technologies like integrative technology platforms represent technological levers to lower the manufacturing costs and increase delivery performance (Tönissen 2014).

Against this background, a deeper understanding of the precise contribution of technological and managerial advances to lower the dichotomous relationships within the four major competitive priorities is likely to prove beneficial in multiple ways. Overall, it may strengthen a company's competitiveness by providing guidance on how to cope with the above-described challenges. In more detail, it may, for example, help managers to decide about investments in advanced manufacturing technologies and the allocation of scarce resources. Taken together, these insights and the resulting potential increase in competitiveness of manufacturing companies in high-wage countries states the overall motivation in developing a technology-oriented theory of production. Therefore, the leading research question is formulated as follows:

> How can the impact of technological advances on the resolution of the dichotomous relationships between the four major competitive priorities cost, quality, flexibility and delivery performance be operationalized and linked with the profitability of a manufacturing company?

12.3 State of the Art

12.3.1 Production Theory Models

Researchers have tried to translate processes around goods transformation into mathematical relationships and laws for centuries. As a main result, production theories comprise the economic management and measurement of transformation processes (Dyckhoff 2006). In this context, production functions are the respective *quantitative relationships between input and output* of production units (Krelle

1969). Following Steven (1998), Fandel (2005) and Brecher et al. (2012), this section gives an overview of production theory development over time, reflecting the state-of-the-art in research.

Nevertheless, it is to be recognized that the attention to production theory and functions in the academic world has unfortunately significantly decreased over the past decades: the number of publications per year fell by 60–70 % from the early 90s to 2010 (based on an indicative search for the terms "production theory" and "production function" in *EBSCO*, *ScienceDirect*, and *WISO*). This development may be partially driven by the fact that the different types of production theories and functions to date have rather addressed specific questions and fields of research, insofar that their applicability in the form of a holistic theory is still missing (Dyckhoff 2006).

Hence, the following examination aims at revealing that throughout the decades focus was—first and foremost—put on enhancing production theory in the field of manufacturing and linking it to classical cost theory. Consequently, aspects of product development and engineering as well as their multifaceted, joint impact together with manufacturing on a company's revenue and earnings side have been widely neglected. Taking the four initially highlighted competitive priorities into account, it will become evident, however, that there is an imperative need to integrate these aspects in modern production theory. Hence, for being able to assess the impact of advances in production management and technologies on company performance, diverse aspects related to quality, flexibility, and delivery performance such as customer requirements, product variants or time-to-market are to be considered (see Sect. 12.4.2). Figure 12.2 gives an overview on the subsequently discussed production theory research streams.

The (*neo*) *classic production functions* were the first efforts to delineate input–output relations in transformation processes. They are referred to as *type A* production functions within the production theory research community and describe relationships at a highly aggregated level (Steven 1998). Turgot (1766) developed

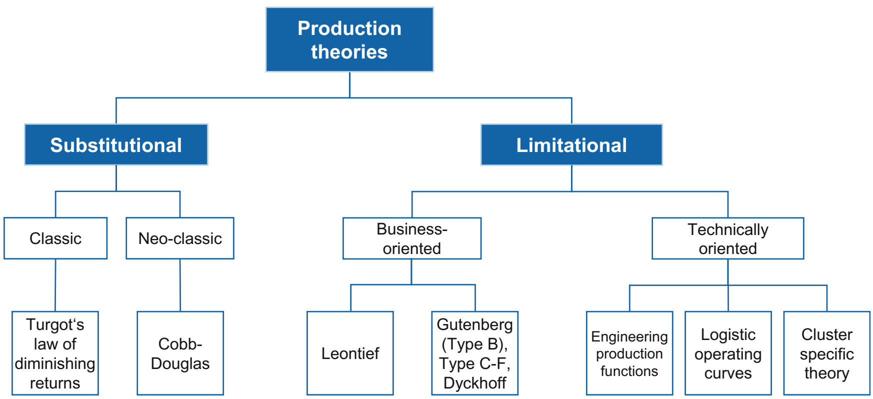

Fig. 12.2 Overview on production theories

what is considered as *the first classic production function* (Schweitzer and Küpper 1997). In an agricultural context, he suggests an s-curve to describe the relation between input factors (labor and seeds) and output (crop). In his law of diminishing returns, increasing marginal returns (economies of scale) are followed by decreasing ones (diseconomies of scale) (Steven 1998). The input factors are combined in a *substitutional relationship*, which means that a certain output quantity can be achieved through different input combinations. On this basis, Cobb and Douglas (1928) delineate *their neoclassic production function* for industrial manufacturing, where output elasticity is constant and the input factors (work and capital) remain substitutional. Although Cobb and Douglas provide empirical evidence for their approach, the substitutability of input factors is often challenged and narrows the usability of (neo) classic production functions for practitioners (Krelle 1969).

Bearing the critique on substitutional relationships in mind, Leontief (1951) posits a *limitational relationship* between production factors. He describes the interaction between these factors as rather constant and shows that beyond a certain point a higher quantity of one input factor has no effect on the output anymore (Fandel 2005). This can be illustrated by an operation at a turning lathe, which would always require at least one employee and a certain quantity of raw material (Krelle 1969). Accordingly, Schweitzer (1990) provides empirical evidence that the vast majority of industrial production processes is based on such limitational factor relations. The major limitation of Leontief's production function is represented by the assumed production conditions which are constant and with only limited comprehension of technical progress (Walter 1969).

In the same research environment as Leontief, Chenery (1949) and Ferguson (1950) formulated their *engineering production functions*, accounting for the so long-neglected natural scientific fundament of production. Although they also assume limitational factor relationships, their theory rather focuses on the technical interaction between input factors and employs scientific laws from chemistry and physics. While economic production functions are typically derived from observed output data, engineering production functions use technical theory and engineering knowledge to predict production data (Wibe 1984). Yet, the high effort for identifying the parameters in the input–output relationship limits the approach's applicability.

Shortly after in 1951, Gutenberg similarly questioned the (neo) classical approach and developed his industrially-oriented production theory (Gutenberg 1983). Some researchers classify it as the *type B production function* (Steven and Blank 2013). In contrast to previous theories, Gutenberg focuses on a more holistic view of the individual firm and accounts for several adjacent management topics, such as cost accounting and revenue management, while integrating important aspects of Leontief's function (Dyckhoff 2006). However, different to Leontief, Gutenberg differentiates input factors into usage factors and consumption factors. Usage factors (e.g., equipment) utilize consumption factors (e.g., materials) for the production of goods, whereby the technical setup and performance influences the output (Fandel 2005). Subsequently, variation is realized by an adjustment of the runtime, quantity of equipment, and machine intensity (Steven 2000). In this respect, machine intensity is defined by technical performance range. Thus, the direct relationship between the input and output quantity from prior theories is partially replaced by an indirect one that takes technical capabilities into account (Fandel 2005). Altogether, Gutenberg's production function can determine the most cost-efficient output of several employed machines across a certain production timeframe.

Several researchers acknowledge Gutenberg's production theory by expanding his approach through add-ons that aim to mitigate weak points of the original theory. In the 1960s, Heinen criticized the direct relationship between technical (intensity) and economic (output) performance and accordingly extends Gutenberg's approach (Schweitzer and Küpper 1997; Heinen 1983). His *type C production function* considers that the technical performance varies over time in certain *modular phases* (i.e., ramp-up phase, processing phase, braking phase, idle state).

Building upon the division of the production process suggested by Heinen, Kloock (1969) introduces his *type D production function* approach (Schweitzer and Küpper 1997). Kloock transfers Leontief's input–output analysis to operations management—in particular, by taking the substitutability of production processes into account (Fandel 2005). The illustration of the production process—either quantitatively through an equation system or matrices and qualitatively through graphs—allows mapping supply relations, and can delineate multilevel as well as cyclical production systems (Steven 1998).

Production functions so far only comprise limited and indirect dynamic elements (e.g., the production phases from Heinen) and can thus be considered static. In order to address this limitation, Küpper's (1996) *type E production function*, developed in 1979, respects the *dynamic interdependencies* between production processes and extends Kloock's input–output analysis by a period index taking the waiting time of work pieces between different production levels into account (Fandel 2005). Matthes' (1979) *type F production function* expands Küpper's dynamic theory by including several additional firm conditions, such as structural interdependencies, financial restrictions, and social aspects (Steven 1998). This allows optimizing whole production systems, but also increases complexity.

After these advancements, the progress and interest on production theory has significantly decreased throughout the last decades (Dyckhoff 2003). Due to the post-Gutenberg attempts to integrate additional production aspects, the production functions became increasingly complex, which restricts their practical applicability. Consequently, most approaches have hardly been empirically examined. In addition, their assumptions are considered to be too narrowly defined to describe realistic production processes (Schneeweiß 2002). Thus, new production technologies can hardly be integrated. Dyckhoff (2003) proposes two potential solutions to refuel the scientific discussion. First, previous theories can be evaluated as specific components of a holistic general theory that has not been defined yet. Second, he posits that new specific theories can help to reanimate the discussion on such a holistic theory. The *technology-oriented theory of production* presented in this book responds to this research call, and aims to deliver insights for specific new technologies to reanimate the general discussion on production theory. However, the proposed theory also provides a framework to anchor the specific assessments in a new general view. Specifically, the theory merges profitability assessments with largely neglected engineering aspects.

Further, Dyckhoff (2006) aims to delineate a general concept for a new general production theory. He integrates a decision-based perspective and proposes the analysis of complex production systems via a system-based view. In addition, he suggests criteria beyond economic as well as social and ecological ones for a holistic assessment. Yet, his concept represents rather a general starting point for further research than a final new theory.

The *production logistic theory* by Nyhuis (1991), Becker and Nyhuis (2015) can be classified as another contribution to the specific production theories. Nyhuis suggests linking several logistic models for a model-based optimization of the whole firm-internal supply chain. One link represents his logistic operating curves model, which delineates the mathematical interaction between work-in-progress goods and output rate as well as workstation range, building on empirical evidence (Nyhuis 1991). By enhancing the model upstream (e.g., supply storage) and downstream (e.g., assembly, customer distribution), it can deliver an optimum for the whole supply chain. However, the integration of these models for a holistic production logistic theory is still in progress (Becker and Nyhuis 2015).

Considering the achievements and development potential of all of these theories, classifying and distinguishing the technology-oriented theory of production within this research area ensues.

12.3.2 Classification of the Technology-Oriented Theory of Production

As already discussed, a variety of different types of production functions have been developed across centuries with the aspiration to explain the distinct realities of production in diverse settings of industrial firms (Fandel 2005). Following this claim, the production theories are classified according to the following dimensions based on extant literature (Bloech et al. 2014; Vossebein 2001; Fandel 2005; Schwalbach 2014): (1) *primary object of analysis*, (2) *input-output relationship*, (3) *consideration of time effects*, (4) *number of product types*, and (5) *technology comprehension*. This section utilizes a five-dimensional framework displayed in Fig. 12.3 to distinguish the technology-oriented theory of production relative to other production functions (with the theories' primary focus highlighted in brackets). With type A neoclassic production functions are referred to. Since our technology-oriented theory of production is limitational, a focus on type B (Gutenberg's approach) and the derived approaches C–F as described in the previous section also follows. Furthermore, Dyckhoff's (2006) suggested production theory given its comprehension of prior limitations and engineering production functions (EPF) due to their consideration of technical aspects is considered.

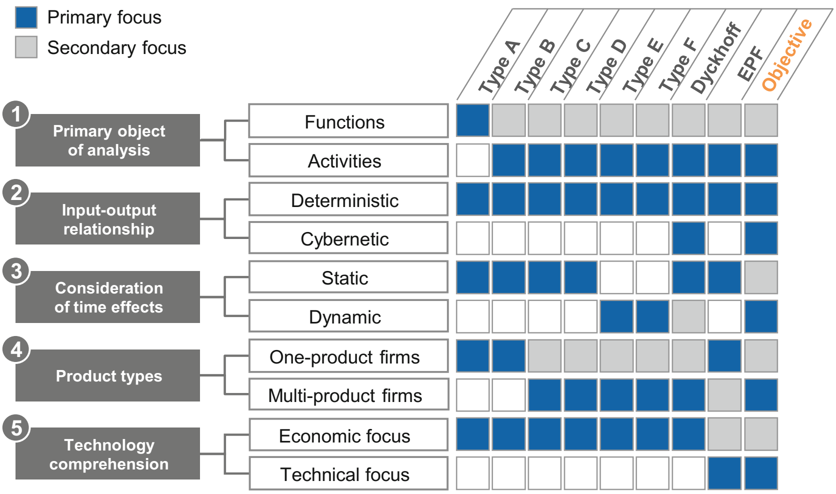

Fig. 12.3 Framework for classification of production theories

Except for type A production functions, all discussed approaches are limitational, which means that individual factors are not interchangeable. As already shown in Fig. 12.2, the technology-oriented theory of production has the *objective* of putting emphasis on real limitational technical aspects, since it is derived from the formal properties of technologies examined in the Cluster's projects.

1. **Primary object of analysis**

Function analysis (*Type A*): Starting point is the mathematical delineation of the productive transformation process. Focus is put on the description, derivation and shaping of the relationship between input and output based on quantitative production functions in a mathematical form (Corsten 2012; Matthes 1996; Fandel 2005).

Activity analysis (*Type B–F, Dyckhoff, EPF*): The field of *activity analysis* was initiated by Koopmans (1951) who defined an activity as "the combination of certain qualitatively defined commodities in fixed quantitative ratios as 'inputs' to produce as 'outputs' certain other commodities in fixed quantitative ratios to the inputs" (S.35). Production theories based on activities are process-oriented in that processes determine the input and output and not vice versa (Dyckhoff 2006). Accordingly, the technology-oriented theory of production has the objective of building upon formal technological properties and their underlying processes (i.e., the Cluster technologies) as a starting point to display a choice between alternative combinations of input and output (Corsten 2012; Kistner 1993).

2. **Input–output relationship**

Deterministic relationships (*Type A–F, Dyckhoff, EPF*): There is a deterministic relationship between input and output assumed so that the latter remains constant over time in the presence of equal input factors and conditions for production

(Schwalbach 2014). Gutenberg (1983) and Heinen (1983) only cover this connection indirectly by integrating more technical factors (e.g., machine intensity) so that the output is not directly related to the input but rather originates from a technical process.

Cybernetic relationships (*Dyckhoff*): The so-called *viable system model* is the most prominent corporate management model of *cybernetic relationships* (Beer 1985). It assumes that each organization consists of several subsystems to survive. The viability of these systems is constituted, in turn, by the ability to adapt to the dynamic environment, maintain a distinct identity, and transfer the meaning of its own actions to third parties (Schuh and Kampker 2011). A *cybernetic decision-oriented framework* has been developed by Dyckhoff (2006). This approach allows for the existence of *self-optimizing production systems*—in contrast to purely *deterministic* open loop input–output models. Such systems are assumed to permanently allow productivity improvements by cybernetic and structural changes in the parameters and conditions (see Part IV). Consequently, the technology-oriented theory of production also aims at including cybernetic aspects (Schuh et al. 2014b).

3. **Consideration of time effects**

Static approach (*Type A–D, Dyckhoff, EPF*): The lapse of time is not considered as an explicit parameter in most theories, but is not neglected (Schwalbach 2014). Instead, static production functions are based upon production theoretical considerations at a specific point in time (Fandel 2005).

Dynamic approach (*Type E, F*): Taking aspects of time into account, *short-term* and *long-term dynamic production functions* are to be distinguished. In the short-run, a number of time effects become relevant which are related to the manufacturing process itself (e.g., capacity constraints requiring the spread of production over time) or logistics (e.g., lot sizes) or storage (e.g., development of inventories over time). In the long-run, focus is put on the change in production conditions and the progress of technology, including learning processes as a special form of technological progress (Schwalbach 2014). As productive relationships are in reality mostly of a dynamic nature, newer production theories such as type E and F have started to explicitly incorporate the factor time. There are several dynamic aspects within the technology-oriented theory of production. Short-term dynamic aspects are, for example, included in the socio-technical learning curve in self-optimizing production systems (see Chap. 8). Long-term aspects are for instance included by assessing the technology impact across the whole product life cycle with a time-to-market approach (e.g., for selective laser melting) and by accounting for iterations to finalize an activity and thus resulting learning effects (see Chap. 2). Nonetheless, similar to stochastic considerations, a comprehensive dynamic production theory is still outstanding.

4. **Product type quantity**

One-product firms (*Type A, B, EPF*): In this case, only one main product is manufactured with several input factors. However, each transformation of input factors normally leads to side- and byproducts in addition to the main products (Dyckhoff 2006).

Multi-product firms (*Type C–F, Dyckhoff*): The term *multi-product* production refers to the creation of several variants of a product in one production system (Dyckhoff 2006). Considering the capabilities of individualized production systems described within the technology-oriented theory of production, infinite product variants are possible and aimed at (see Part I). Accordingly, the technology-oriented theory of production constitutes, to some extent, a novel *infinite-product environment*.

5. **Technology comprehension**

Economic focus (*Type A–F, Dyckhoff*): Most production theories view production technology at a highly aggregated level, mainly focusing on economic aspects. Their production functions are mainly derived from observed output data, considering the physical and chemical transformations as a 'black box' (Wibe 1984).

Technical focus (*EPF*): Production theories with a technical focus specifically integrate natural scientific laws in their production optimization. Building up on the engineering production functions by Chenery (1949) and Ferguson (1950), the technology-oriented theory of production uses engineering knowledge (e.g., fluid mechanics, Ref. ICD A3, Chap. "Application Plastics Profile Extrusion") for each production technology to yield an optimal factor combination. Yet, it still considers economic aspects by using cost and revenue items to assess the economic viability of a technology. Specifically the technology dichotomies of the technology-oriented theory of production aim at linking the economic optimization with production system configurations.

12.4 Results

In conclusion to the clarified state-of-the-art concerning production theory above, the technology-oriented theory of production aims at delivering meaningful explanatory contributions for operations managers and researchers with regards to all of the four initially introduced crucial operational capabilities of manufacturing firms: cost, quality, flexibility, and delivery performance.

Contrarily to classical production theories, which have put strong emphasis on the cost side and on the derivation of production functions from a purely economic perspective, this theory strives to integrate the following additional aspects:

Classifying production systems as complex, socio-technical constructs for which prediction is only partly possible. On the one hand, our theory has thus the objective to build upon dynamic, deterministic models in a multi-product setting aiming at the identification of subsystems and their predictable interrelationships to reduce complexity [e.g., Ref. ICD A]. On the other, it aims at incorporating cybernetic aspects identifying phenomena and structures to master complexity [e.g., Ref. ICD D].

In this context, the aspects of quality, flexibility, and delivery performance are, for instance, addressed by the incorporation of the Kano-model of quality, product variants, and time-to-market respectively, which are jointly linked to the earnings and revenue side of a manufacturing company (see Sect. 12.4.1).

Finally, the derived theory considers product engineering processes and their related costs next to pure manufacturing functions. For this purpose, for example, product and tool development costs from the preceding development phase are included in our functions (see Sect. 12.4.3).

Taken together, the classification of our theory delineated above is subsequently operationalized in a profitability assessment that puts emphasis on real limitational technical aspects, since it is derived from the formal properties of technologies examined in the Cluster's projects.

Following the main research question from Sect. 12.2, these properties were linked with constituent parameters (e.g., product variants commonalities, numerical acceleration, learning rates, quality fulfillment) that affect all four competitive priorities (see Fig. 12.4). Further, the resulting profitability metric is a function of these constituent parameters.

This link between technological advances, the four competitive priorities, and a general profitability function shall support policy makers in their alignment of strategic priorities and investments in advanced manufacturing technologies. A detailed description of the profitability relationships is described in the following sections.

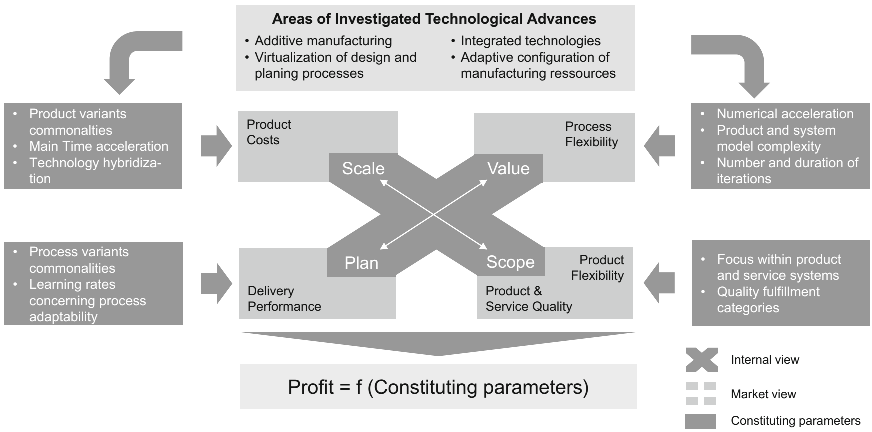

Fig. 12.4 Exemplary constituting parameters within the research framework of the technology-oriented theory of production

12.4.1 Operationalization of Technological Advances Within the CoE Towards Their Impact on Profitability

As Eq. (12.1) shows, profitability can be described as a function of sales and costs that, in turn, are affected by particular drivers:

$$\begin{aligned}\text{Profit} &= \text{Sales} - \text{Fixed Costs} - \text{Variable Costs}\\ &= \underbrace{p_{\mathrm{q}} \cdot x_{\mathrm{sv}}}_{\text{Sales}} - \underbrace{\sum_{j=1}^{n} C_j}_{\text{Fixed Costs}} - \underbrace{\left[t_{\mathrm{u}} \cdot (c_{\mathrm{mh}} + c_{\mathrm{l}}) + C_{\mathrm{t}} + C_{\mathrm{m}}\right] \cdot x_{\mathrm{pv}}}_{\text{Variable Costs}},\end{aligned} \tag{12.1}$$

x_{sv} units sold of all product variants,
x_{pv} units produced of all product variants,
p_{q} price depending on the product and service quality,
C_j fixed costs of one cost block/activity j (e.g. product development, tool development, …),
n number of activities,
t_{u} unit time [h],
c_{mh} machine hourly rate,
c_{l} labor costs per hour,
C_{t} tooling costs,
C_{m} material costs.

Thus, in order to derive the cluster technologies' profitability, their impacts on the profitability drivers, such as product variety and unit time, were analyzed. Greater impacts on those drivers were identified and particularly regarded as primary or secondary driver and summarized in a driver tree (see Fig. 12.5). Through analysis and consolidation of the primary and secondary drivers of all technologies, overarching equations for the profitability measures concerning sales and costs have been derived. So far, the derived equations present a first conceptual starting point and have to be validated and if necessary adapted. In the following, the impact of the profitability drivers of the different technologies on the three summands Sales, Fixed Costs and Variable Costs are modeled by means of equations to derive the technology-oriented theory of production.

12.4.2 Operationalization Towards the Impact on Sales

The first element of the profit equation is sales, which is a function of the sold product quantity and the respective price per unit sold. The sales quantity and willingness to pay a certain price are influenced by *product quality*, *number of*

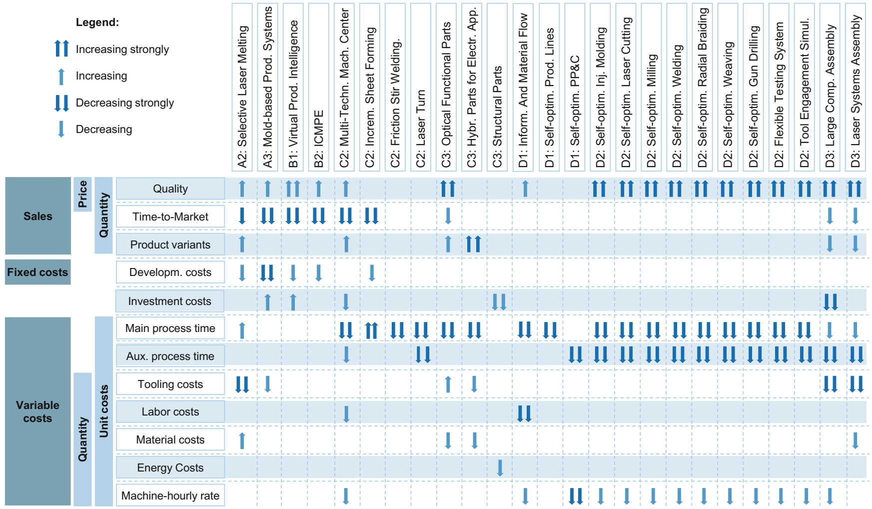

Fig. 12.5 Impact of the cluster technologies on the profitability drivers

product variants and the *time-to-market*. These factors also coincide with the competitive priorities quality and delivery. A further competitive priority, flexibility, is also addressed via the number of product variants that allow a company to flexibly address the customer's requirements. In the following, the sales drivers are discussed in detail.

Quality

Finding an accurate and applicable mathematical description of the concept of *quality* has occupied scientists for decades (e.g. Krelle 1969). Quality can be measured from several points of view (e.g., product, user, manufacturing-based) (Garvin 1988). In order to consider the impact of quality on profitability, it is important to take the system boundaries of a company into account, since some technologies only influence quality *within* the company. For instance, the cluster domain of self-optimizing production technologies mainly focuses on the quality of the manufacturing process. Still, this increase in process quality (e.g., increased drilling speed) does not necessarily influence the customer's willingness to pay for the final product and thus has an impact mainly on profitability from the cost side. From a sales perspective, quality is interpreted as a factor to describe a customer's willingness to pay. Thus, quality describes an individual matter and is determined by the ability of a product to satisfy a customer's preferences and requirements (Ross and Perry 1999; Omachonu and Ross 2004). The price basis and the price premium-terms scale the basic price p_0. The idea for determining the price in this manner, is based on the Kano model (Kano et al. 1984), which considers the dependency of different product features and customer satisfaction (see Fig. 12.6).

The different types of customer requirements consisting of basic expectations, satisfiers and delighters of this model are implemented in the Eq. (12.3) by the

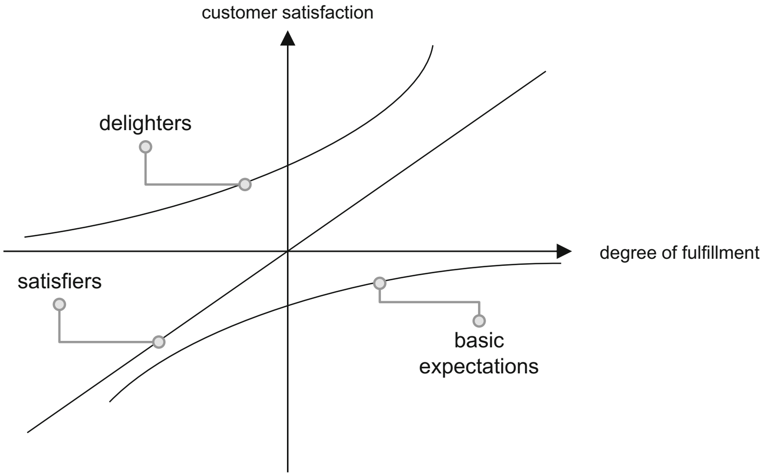

Fig. 12.6 Types of requirements according to the Kano model (Burns and Evans 2000)

factors $e_{\mathrm{b}}, e_{\mathrm{s}}, e_{\mathrm{d}}$. In this context, basic expectations are requirements, which have to be fulfilled and are only "mentioned by the customer, when absent" (Burns and Evans 2000) (e.g., a leaking fuel pump). Satisfiers are requirements such as the engine power. A higher fulfillment of these attributes leads to a higher customer satisfaction. Unexpected product attributes help to distinguish a product from its competitors and address latent customer requirements (Burns and Evans 2000). If basic expectations are fulfilled, customers are only willing to pay the basic price, whereas a non-fulfillment reduces this willingness. Hence, the value of customer satisfaction due to basic expectation $e_{\mathrm{b},i}$ ranges from −1, causing no willingness to pay ($p_{\mathrm{q}} = 0$), to 0, describing the customer's willingness to pay the basic price.

Satisfiers and delighters, in contrast, generate a price premium (Weller and Kleer 2015). In addition to the influencing factors derived from the Kano-model, π_p and π_s are integrated in the *price basis* and *price premium*. π_p and π_s consider the different dimensions of quality (Molina-Castillo et al. 2013), which are on the one hand perceived through the product performance and on the other hand through the service accompanied with the product in terms of a product service system (Belz et al. 1997).

For both quality dimensions different types of requirements exist. For instance, a delighter within the service dimension might be the overnight delivery of spare parts for a product. Especially within an Industrie 4.0 environment, services addressing smart data become more relevant and make up a viable feature for a product. Equation (12.2) describes the impact of quality on the basic price of a product:

$$p_{\mathrm{q}} = p_0 \cdot \underbrace{\left[1 + \left(e_{\mathrm{b},p} \cdot \pi_p + e_{\mathrm{b},s} \cdot \pi_s\right)\right]}_{\substack{\text{price basis due to} \\ \text{basic expectations}}} \cdot \underbrace{\left\{1 + \left[\left(e_{\mathrm{s},p} + e_{\mathrm{d},p}\right) \cdot \pi_p + \left(e_{\mathrm{s},s} + e_{\mathrm{d},s}\right) \cdot \pi_s\right]\right\}}_{\substack{\text{price premium due to} \\ \text{satisfiers and delighters}}} \tag{12.2}$$

p_{q} price depending on the product and service quality;
p_0 basic price of a product, which fulfills basic expectations;
$i = p$ quality induced due to product performance;
$i = s$ quality induced due to service performance;
π_i focus within the product service system between product performance π_p and service performance π_s, $\pi_s + \pi_p = 1$; with $\pi_s, \pi_p \geq 0$ and $\pi_s, \pi_p \in \mathbb{R}$;
$e_{\mathrm{b},i}$ customer satisfaction due to fulfillment of basic expectations; with $-1 \leq e_{\mathrm{b},i} \leq 0$ and $e_{\mathrm{b},i} \in \mathbb{R}$;
$e_{\mathrm{s},i}$ customer satisfaction due to fulfillment of satisfiers; with $e_{\mathrm{s},i} \geq 0$ and $e_{\mathrm{s},i} \in \mathbb{R}$;
$e_{\mathrm{d},i}$ customer satisfaction due to fulfillment of delighters; with $e_{\mathrm{d},i} \geq 0$ and $e_{\mathrm{d},i} \in \mathbb{R}$.

Within the Cluster of Excellence, several technologies strive to improve the quality in terms of individualization and better product performance. For example, the multi-technology platform (see Chap. 6) and monolithic optics affect the customer's willingness to pay due to enhanced individualization of the product (see Chap. 7). Selective laser melting is one further technology, which supports individualization. Due to the possibility to produce a product without a specific tool directly from CAD-data, there are nearly no limits to individualize a product for a customer (see Chap. 2).

Time-to-Market

The time-to-market is the time span from the start of development until the introduction of a product to the market (Cohen et al. 1996). As increasing innovation and time pressure based on shortening product and process lifecycles define the business environment of today's companies (Eversheim 2007; Eversheim and Schuh 2005), time-to-market represents a key competitive factor (Millson 1992; Griffin 1993; Calantone and Di Benedetto 2000). Despite this increasing market pressure, previous production theories largely neglect time-to-market as an issue (Dohmen 2003). In general, a shorter time-to-market enables a company to generate more profit by a deeper exploitation of the window of demand for a certain product. Furthermore, it is possible to create competitive advantages due to first mover advantages (Kerin et al. 1992). The optimal time-to-market depends on a company's market power, strategy and the performance of the product. Consequently, a tradeoff exists between the time-to-market and the product performance. Since a shortened time-to-market can affect the product performance negatively (Calantone and Di Benedetto 2000), generalizing on the impact of time-to-market on sales is hardly possible. Nevertheless, its composition and potential to positively influence sales are discussed in the following.

Time-to-market is determined by the duration of the activities [e.g., engineering, evaluation and prototyping, tool development, factory planning, and process development (Göpfert 2009; Feldhusen and Grote 2013) until market introduction. Furthermore, total duration is determined by the number of iterations required to finalize respective activities (see Eq. (12.3)] (e.g., to design a tool, which is able to produce the final product in a required quality). In this context, the duration to complete one activity decreases with each iteration due to learning effects (Westkämper 1997; Niemann 2007). Equation (12.3) does not have a direct link to the profit formula introduced before. Nevertheless, a shorter time-to-market helps a company to exploit the window of demand and subsequently increase the units sold.

$$\mathrm{TtM} = \sum_{j=1}^{n} t_j = \sum_{j=1}^{n} t_{j,0} \cdot I_j^{1-b_j}, \tag{12.3}$$

TtM Time-to-Market,
n number of activities,
t_j duration of activity j (e.g. product development, tool development…),
$t_{j,0}$ basic duration of activity j,
I_j number of iterations to finalize activity j,
b_j learning rate of one iteration of activity j; with $0 \leq b_j$ and $b_j \in \mathbb{R}$.

There are two levers to accelerate the time-to-market. First, it is possible to shorten the duration of the different activities and, second, enhanced parallelization of activities decreases the total time-to-market. Both are discussed in the following.

Acceleration of Activities t_j

To accelerate an activity, it is possible to increase the learning rate b_j, to shorten the basic duration of the activity $t_{j,0}$, or to reduce the number of iterations I_j. Simulation becomes increasingly important especially within an Industrie 4.0 environment—and beneficial due to enhanced simulation possibilities like processing power or increased simulation speed (Schuh et al. 2014b, 2015). Equation (12.4) describes the impact of simulation on the duration for developing a tool, as identified (see Chap. 3). The impact of simulation depends on the one hand on the numerical acceleration and on the other hand on the complexity of simulation. Based on simulation it is possible, for example, to decrease the duration of tool development depending on acceleration (e.g., for the identification of critical design features) due to simulation (Siegbert et al. 2014) (see Chap. 3). Another example is the increased speed for the development of new materials (see Chap. 5). With a maximum support of simulation $a \rightarrow 1$, the duration can be minimized.

$$T_{\mathrm{T}} = t_{\mathrm{T},0} \cdot \underbrace{\left(1 - \frac{a}{d+1}\right)}_{\substack{\text{Impact factor}\\ \text{of simulation}}} \cdot I_{\mathrm{T}}^{1-b_{\mathrm{T}}}, \tag{12.4}$$

T_{T} total duration of tool development,
a numerical acceleration factor; with $0 \leq a < 1$ and $a \in \mathbb{R}$, $a = 0$, for conventional tool development and $a \to 1$ as threshold value of acceleration,
d complexity of simulation, with $d \geq 0$ and $d \in \mathbb{R}$, $d = d(\text{product complexity, model, process, \#target values})$,
$t_{\mathrm{T},0}$ basic duration of tool development,
b_{T} learning rate when developing a tool; with $0 \leq b_{\mathrm{T}} \leq 1$ and $b_{\mathrm{T}} \in \mathbb{R}$,
I_{T} number of tool development iterations.

The complexity of simulation, in this context, depends on the product complexity, the material model, the process, or the number of target figures. Simulation also increases the learning rate and decreases the number of development iterations driven by enhanced learning, since iterations can be executed more target-oriented (Kellner et al. 1999; Schuh et al. 2014b). In the context of the technology-oriented theory of production, all learning rates are derived from the learning rate according to Wright. This learning rate relates the production costs for a product depending on the cumulated number of products produced (Wright 1936) and states that with an increasing number of units produced, the costs per piece decrease.

Parallelization of Activities

Activity parallelization as a lever to accelerate time-to-market is well documented within the scientific community (Dean and Susman 1989; Karagozoglu 1993; Millson 1992; Murmann 1994; Takeuchi and Nonaka 1986; Calantone and Di Benedetto 2000). In the context of the technologies described in this book, parallelization is enhanced by approaches, such as selective laser melting, plant simulation or numerical simulation of tools. For instance, selective laser melting allows directly producing prototypes at the beginning of the development process. These prototypes can then be used to accumulate customer feedback and to validate the product, which parallelizes and integrates these steps (see Chap. 2). Numerical simulation supports the parallelization of the product and the tool development process. On the basis of product design data, it is possible to simulate the tool in order to start the tool development process shortly after the product development process (see Chap. 3).

Product Variants

Next to the quality and the time-to-market, the number of product variants represents another factor that has an impact on the quantity of units sold. In general, an increasing number of variants helps to address more individual customer needs, which can lead to better market penetration and thus an increasing market share

(Weller et al. 2015). For example, enhanced individualization can be achieved by additive manufacturing technologies allowing a company to address specific customer needs without great engineering or adaption effort (Weller et al. 2015) (see Chap. 2). Next to additive manufacturing, technologies, such as multi-technology platforms (see Chap. 6) or technologies for the production of integrated electrical parts (see Chap. 7), support individualization and thus enable a company to increase the number of product variants for a greater market share. Nevertheless, the marginal utility of an increasing number of product variants is negative since the product variants cannot be sufficiently differentiated from one another anymore. This can even lead to the so called "Paradox of Choice" (Schwartz 2005), which describes the effect of decreasing customer satisfaction during the buying process if too many variants are available. Hence, the customer is not able to make a founded choice regarding the product variants suitable for his requirements. Another reason for the decreasing utility of further product variants, lies within the restricted market size for one product type (Draganska and Jain 2005).

12.4.3 *Operationalization Towards the Impact on Fixed Costs*

After examining the sales drivers, the next section starts the discussion on the cost side by elaborating fixed costs. Fixed costs consist of several cost blocks (e.g., tool development costs, product development costs (Stocker 2002), costs for the infrastructure (Stelling 2009). Comparable to the factors influencing sales, the factors influencing the fixed costs can also be matched with the competitive priorities. Next to the competitive priority costs, the factors described in the following also describe the influence on the delivery due the acceleration of activities. Technologies within the Cluster of Excellence specifically address product development costs, tool development costs and costs for the infrastructure, which will be described in the following.

Product Development Costs

Regarding the discussed technologies, the development costs for a product is primarily determined by engineering costs and prototyping costs as shown in Eq. (12.5):

$$C_{\mathrm{dev}} = \left(\overline{c_{\mathrm{e}}} \cdot n_{\mathrm{pv}}^{1-b_{\mathrm{pv}}} + \overline{c_{\mathrm{prot}}} \cdot n_{\mathrm{pv}}\right) \cdot I_{\mathrm{P}}^{1-b_{I}}, \tag{12.5}$$

C_{dev} development costs for all product variants,
$\overline{c_{\mathrm{e}}}$ average engineering costs per iteration for one product variant,
$\overline{c_{\mathrm{prot}}}$ average prototyping costs per iteration for one product variant,

b_{pv} learning rate due to the number of product variants; with $0 \leq b_{\mathrm{pv}} < 1$ and $b_{\mathrm{pv}} \in \mathbb{R}$,
I_{P} number of iterations to develop product variant p,
b_I learning rate in the development of product variant p due to iterations; with $0 \leq b_I < 1$ and $b_I \in \mathbb{R}$,
n_{pv} number of product variants.

Product development costs can be estimated by the total engineering time multiplied by the average wage of the involved employees plus the prototyping costs. Similar to the costs for tool development, product development costs highly depend on the number of iterations and the number of product variants. The iterations and the derivation of additional variants are also subject to a learning rate. As an example, the selective laser melting technology supports rapid prototyping, which helps to gather feedback for the next development iteration. Thus, an iteration can be executed more target oriented regarding the customer requirements, which decreases the costs per iteration (Schuh et al. 2015). Through integration of such technologies the learning rate can also be influenced via enhanced learning (see Chap. 2).

Tool Development Costs
First, the development costs for a tool consist of engineering costs, process planning costs, manufacturing costs as well as assembly costs for the initial tool itself (Schuh et al. 2014c). Second, they comprise iterative adaption costs to ensure that the tool can manufacture qualitatively adequate products (Eversheim and Klocke 1998). When the tool is tested and the resulting products fail to meet the specified requirements, the tool has to be adapted and the procedure has to be iteratively repeated until the requirements are met. Therefore, the development costs highly depend on the number of iterations needed to finalize the tool (see Chap. 3). Tools are composed of certain tool components, e.g. arbor, shell and cutter in cutting processes, whereas the difference between different tool component types n is ascertained in the following.

$$c_{\mathrm{tv}} = \sum_{i=1}^{n} \underbrace{\left\{ c_{\mathrm{T},0,i} + \underbrace{\left[\left(t_{\mathrm{s},i} + t_{\mathrm{p},i}\right) \cdot \left(c_{\mathrm{r},i} + c_{\mathrm{mh},i} + c_{\mathrm{p},i}\right)\right] \cdot I_{\mathrm{T},i}}_{\substack{\text{Process costs} \\ \text{for one tool variant}}} + \underbrace{\overline{c_{\mathrm{e,T},i}} \cdot \left(I_{\mathrm{T},i} - 1\right)^{1-b_{\mathrm{ta},i}}}_{\substack{\text{Adaption costs} \\ \text{for one tool variant}}} + \underbrace{\overline{c_{\mathrm{s},i}} \cdot \left(I_{\mathrm{T},i} - 1\right)}_{\substack{\text{Material costs} \\ \text{for one tool variant}}} \right\}}_{\text{Total development costs for one tool variant}} \cdot \underbrace{\underbrace{\left(\frac{n_{\mathrm{pv}}}{n_{\mathrm{tT},i}}\right)^{1-b_{\mathrm{d}}}}_{n_{\mathrm{tv}}}}_{\text{synergy factor}}, \tag{12.6}$$

C_{tv} costs for all tool variant due to the number of product variants,
n number of different tool component types,
$c_{\mathrm{T},0,i}$ manufacturing and engineering costs for tool component type i,
$t_{\mathrm{s},i}$ set up time for validation [h],
$t_{\mathrm{p},i}$ production time for validation [h],
$c_{\mathrm{r},i}$ forfeited revenue per hour on machine,
$c_{\mathrm{mh},i}$ machine hourly rate,
$c_{\mathrm{p},i}$ personnel costs per hour,
$\overline{c_{\mathrm{e,T},i}}$ av. engineering costs of tool component type i due to adjustments after one iteration,
$I_{\mathrm{T},i}$ number of iterations needed to complete tool component type i,
$b_{\mathrm{ta},i}$ learning rate of adjustment of tool component type i; with $0 \le b_{\mathrm{ta},i} < 1$ and $b_{\mathrm{ta},i} \in \mathbb{R}$,
$\overline{c_{\mathrm{s},i}}$ av. material costs due to wasted material/scrap produced for validation for tool component type i,
n_{pv} number of product variants,
$\overline{n_{\mathrm{tT},i}}$ average number of variants producible with tool component type i,
b_{d} learning rate of designing; with $0 \le b_{\mathrm{d}} < 1$ and $b_{\mathrm{d}} \in \mathbb{R}$,
n_{tv} number of tool variants.

The expense of one tool variant is estimated by the initial manufacturing and engineering, process, adaption and material costs associated with its validation. Process costs emerge with each iteration and consist of operational expenses for the machine used, personnel costs for the validation and the forfeited revenue. The operational and personnel costs can be determined by the machine hourly rate, the labor costs and the occupation time of the machine, whereas the forfeited revenue is calculated based on the productivity of the machine. The material costs result from the waste caused during validation, as the manufactured product cannot be sold, whereas the adaption costs can be seen as fixed costs. Both material and adaption costs occur one time fewer than the total number of iterations, since no adaptations are needed for the first iteration and products of the final iteration can be sold. In this context, it is plausible that the iteration costs are subject to a learning rate, since adjustments become less extensive with each additional iteration. As for the validation of a tool after each iteration, the amount of final product needed remains nearly constant, and material costs are not subject to a learning rate.

Considering that one tool variant can only be used to manufacture a certain amount of product variants, additional tool variants are needed to manufacture all product variants within the portfolio. The number of needed tools can be determined by dividing the number of product variants by the number of product variants producible with one tool variant. Driven by learning rates and the possibility of deriving further variants from existing tools, the costs of developing one additional tool decrease with the number of existing variants (see Chap. 3).

Costs for Infrastructure

The type of fixed infrastructure costs referred to in this section mainly result from providing the required setting (e.g., property, plant, and equipment (PPE) including necessary work to ensure its capability of operation) and capabilities (e.g., workforce training) for a specific production technology. Consistent with our framework, however, a profitability assessment view on these costs is being taken—rather than merely replicating their accounting treatment. Three types of infrastructure costs mainly drive technology profitability: costs for property, plant, and equipment (e.g., buildings), the costs for information technology (IT), and the costs for training and education for employees. The costs for IT consist of all costs for software and computer systems supporting the evaluated production technology. These costs correlate with the degree or quality of planning and simulation (see Chap. 4). The costs for the infrastructure mainly depend on the required flexibility of the machine or production system (see Chap. 6). At this point a further equation is not introduced, as the infrastructure costs do not lie within the scope of this production theory.

12.4.4 Operationalization Towards the Impact on Variable Costs

The final cost component is represented by variable costs. Five main drivers of variable costs were identified: time per unit, machine hourly rate, labor costs, tooling costs and material costs [see Eq. (12.7)].

$$C_\mathrm{v} = t_\mathrm{u} \cdot (c_\mathrm{mh} + c_\mathrm{l}) \cdot x + C_\mathrm{t} + C_\mathrm{m}, \tag{12.7}$$

C_v variable costs,
t_u time per unit [h],
c_mh machine hourly rate,
c_l labor costs per hour,
C_t tooling costs,
C_m material costs,
x units of all product variants.

One factor of the variable costs is the time per unit defined in accordance with Klocke et al. (2011). Time per unit is a sum of the basic time and additional time in which the operation is interrupted by irregular events like resource procurement, and the recovery time of workers during which the machine stands still. The basic time can be further divided into main process time and auxiliary process time (Pressmar 1971 (2013)).

Due to the focus of technologies in high-wage countries, where salaries are relatively high, labor costs have a large impact on variable costs. In this regard, the importance and indispensability of human labor is emphasized. Even if future technologies and processes become more efficient, it is assumed that workers' tasks will expand or change rather than be reduced. For this reason labor costs will not be specified any more.

Tooling costs are usually included in the machine hourly rate (Kaplan 1990). Since tools are subject to wear and tear, depending on condition and intensity of use, it is reasonable to consider tooling costs separately (VDI 1994) as shown in Eq. (12.7). How the discussed technologies, particularly main process time, auxiliary process time, tooling costs and material costs are affected will be presented in the following.

Main Process Time

Along the process chain, main process time can be subdivided into main time for primary shaping, forming, cutting, joining, coating and material property change (DIN 8580). The main process time primarily depends on physical and kinematic parameters. In addition, the assumption is that manufacturing processes come along with learning effects with an increasing produced quantity resulting from process experience. Therefore, all parameters of the following exemplarily specified main process times for primary shaping, forming, cutting and joining—except for quantity x and learning rate b, relate to the first product produced.

In primary shaping processes such as molding, the main process time $T_{\mathrm{m,p}}$ depends on the duration of the formation of the microstructure to be manufactured (see Chaps. 3 and 5). The primary shaping time is the volume of the material V divided by the build-up rate $\dot{V}$ which in return depends on the build-up length l and width w and on the velocity for building-up $v_{\mathrm{p},i}$. By simulating casting processes, the optimal casting velocity for the formation of a specific microstructure can be determined in order to shorten casting time (see Chap. 3). With an increasing cumulated quantity x, the learning rate b_{p} may positively influence the velocity for building up, because of more process experience. As primary shaping technologies procedurally differ widely, the following formula needs to be adapted for each particular case.

$$T_{\mathrm{m,p}} = \sum_{i=1}^{n_{\mathrm{pv}}} \frac{V}{\dot{V}} \cdot x_i^{1-b_{\mathrm{p}}} = \sum_{i=1}^{n_{\mathrm{pv}}} \frac{V}{v_{\mathrm{p},i} \cdot l \cdot w} \cdot x_i^{1-b_{\mathrm{p}}}, \tag{12.8}$$

$T_{\mathrm{m,p}}$ main time for primary shaping,
n_{pv} number of product variants,
V volume of material (incl. supports) [cm^3],
$\dot{V}$ build-up rate [cm^3/h],
x_i accumulated quantity of units of product variant i,
$v_{\mathrm{p},i}$ velocity (of the first product produced) for building-up,
l build-up length,
w build-up width,
b_{p} learning rate of shaping; with $0 < b_{\mathrm{p}} \leq 1, \ \ b_{\mathrm{p}} \in \mathbb{R}$.

In forming processes the main forming time $T_{\mathrm{m,f}}$ is a sum of all succeeding forming steps p needed for all variants n_{pv}, whereas forming steps may consist of several forming iterations n_{f}. By cleverly arranging different forming technologies, the whole process time can be reduced. One example is the sequential arrangement of fast stretch forming and precise, incremental sheet forming (see Chap. 6). The larger the product, the more forming iterations n_{f} are usually required. Forming time within one forming iteration depends on the length of the forming path l_{f} and the forming velocity v_{f}. Moreover, it is presumed that the main process time decreases with an increasing accumulated quantity x due to the learning rate b_{f} in that more process experience that may come along with higher velocities than the velocity v_{f} of the first product produced (see Chap. 6).

$$T_{\mathrm{m,f}} = \sum_{i=1}^{n_{\mathrm{pv}}} \sum_{j=1}^{n_{\mathrm{p}}} \sum_{k=1}^{n_{\mathrm{f}}} \frac{l_{\mathrm{f},i,j,k}}{v_{\mathrm{f},i,j,k}} \cdot x_i^{1-b_{\mathrm{f}}}, \tag{12.9}$$

$T_{\mathrm{m,f}}$ main time for forming,
n_{pv} number of product variants,
n_{p} number of forming steps,
n_{f} number of forming iterations,
$l_{\mathrm{f},i,j,k}$ length of forming path in forming iteration k of process step j of product variant i,
$v_{\mathrm{f},i,j,k}$ forming velocity (of the first product produced) in forming iteration k of process step j of product variant i,
x_i accumulated quantity of units of product variant i,
b_{f} learning rate of forming; with $0 < b_{\mathrm{f}} \leq 1, \quad b_{\mathrm{f}} \in \mathbb{R}$.

In cutting processes, the total main process time $T_{\mathrm{m,c}}$ depends on all required cutting steps n_{p} for all variants n_{pv} [see Eq. (12.10)]. Hybrid machining, such as parallel cutting and deburring, reduces the number of cutting steps and can thus minimize the main time $T_{\mathrm{m,c}}$ (see Chap. 6). The main time within one cutting process is a function of the length of the feed path l_{f} and cut length l_{c} divided by the feed velocity v_{f}, cutting velocity v_{c} respectively (Klocke et al. 2011).

There exist different influencing factors on the above-described cutting parameters. One factor is the product size: The larger the product is, the more feeds n_{f} are required. Product complexity is another impact factor that can be measured as number of shapes and structures to be integrated into the product (Scheffer et al. 2003). For most manufacturing technologies it can be said, the more complex the product is, the longer the duration of the cutting process is. In order to reduce the main time, manufacturing technologies like additive manufacturing are needed, which are mainly independent of product complexity in terms of time (see Chap. 2). A third factor influencing the aforementioned process parameters—and therefore the main time—is process stability which determines the highest possible cutting speed v_{c} (Hermans and Den Ouden 1999). More stable processes can usually be conducted at higher velocities and therefore reduce the main process time (see Chap. 9).

By enhancing process control and using simulation tools the stability of the process can be increased (see Chaps. 4 and 9). As in the other manufacturing processes, it is believed that the feed and cutting velocity of the first product produced are positively influenced by the learning rate b_{fc} and may decrease with an increasing accumulated quantity x (Biskup 2008).

$$T_{\mathrm{m,c}} = \sum_{i=1}^{n_{\mathrm{pv}}} \sum_{j=1}^{n_{\mathrm{p}}} \left(\sum_{k=1}^{n_{\mathrm{f}}} \frac{l_{\mathrm{fe},i,j,k}}{v_{\mathrm{fe},i,j,k}} + \sum_{l=1}^{n_{\mathrm{c}}} \frac{l_{\mathrm{c},i,j,l}}{v_{\mathrm{c},i,j,l}} \right) \cdot x_i^{1-b_{\mathrm{fc}}}, \tag{12.10}$$

$T_{\mathrm{m,c}}$ main time for cutting processes,
n_{pv} number of product variants,
n_{p} number of cutting steps,
n_{f} number of feeds,
n_{c} number of cuts,
$l_{\mathrm{fe},i,j,k}$ length of feed path in feed iteration k of process step j of product variant i,
$v_{\mathrm{fe},i,j,k}$ feed velocity (of the first product produced) in feed iteration k of process step j of product variant i,
$l_{\mathrm{c},i,j,l}$ cutting length in cutting iteration l of process step j of product variant i,
cutting speed (of the first product produced) in cutting iteration l of process step j of product variant i,
x_i quantity of units of product variant i,
b_{fc} learning rate of feed and cutting; with $0 < b_{\mathrm{fc}} \leq 1,\ \ b_{\mathrm{fc}} \in \mathbb{R}$.

Procedurally, joining processes like welding and braiding differ widely. Hence, a general formula is not provided. However, there are common factors that influence the joining time. One factor is the joining velocity, which correlates with the process stability (Hermans and Den Ouden 1999). In metal arc welding, for instance, higher process robustness through process control leads to higher welding velocities by simultaneously ensuring the joining quality (see Chap. 9). Furthermore, joining time is often affected by product complexity. One example is braiding, a textile joining process where the joining velocity depends on the complexity of the geometry to be manufactured (DIN 8593-5, see Chap. 9). Hybrid manufacturing processes, such as in-mold-metal-spraying, can even render joining processes redundant. For instance, the integration of plastics/metal hybrid parts for electrical applications is partly accomplished by welding or riveting. With the aid of the process technology In-Mold-Metal-Spraying—first spraying a metallic layer in a mold's surface and then injecting plastic into the mold—the joining of the plastic/metal parts is already completed during primary shaping (see Chap. 7). Finally, the main process time for joining is positively influenced by a learning rate resulting from more process experience and higher velocities with increasing quantity.

Auxiliary Process Time

The auxiliary process time includes all indirect processes that are needed for manufacturing, such as tool change, workpiece change, clamping, measuring, and aligning (VDI 1994). Since the tool is not engaged in the material during this time and therefore does not add value, the auxiliary process time needs to be minimized to increase productivity. Auxiliary process times are particularly dependent on organizational aspects (e.g., the optimal choice of batches in case of different modular variants). To reduce non-productive auxiliary time in one machine, jobs that require the same tool adjustments, resources and machining programs are united to batches (Weustink et al. 2000). The number of batches is the quantity of units divided by the average lot size (Goyal 1978).

The time for workpiece change depends on the availability and on the condition of the workpiece to be processed. Idle times resulting from non-available workpieces or workpieces that are not in the optimal operating temperature lead to the prolongation of auxiliary time. Organizational methods like lean production and simulations of production control can help optimize material flows and job scheduling to ensure availability and thus shorten through-put times (see Chap. 8). The optimal condition of workpieces on the other hand can be resolved technologically. By parallelizing heating or hardening technologies with machining technologies, waiting times for improper workpieces can be saved. An alternative for reducing the time of workpiece exchanges are multi-technology platforms. They render the workpiece exchange redundant, since subsequent process steps are integrated into one machine and the workpiece does not need to be transferred before the subsequent process step (see Chaps. 6 and 7).

In addition, increasing automation in machine adjustment for specific product variants can reduce manual clamping, measuring or aligning, and therefore reduces auxiliary time. For instance, the automated setup process of weaving machines automatically calculates and adjusts the optimal warp tension with the aid of sensors and thus reduces auxiliary time (see Chap. 9).

Tooling Costs

As tools are exposed to continuous wear and therefore need to be replaced after tool life, including tooling costs in the variable costs instead of in the machine hourly rate [see Eq. (12.11)] is recommended. Tools are required for molding, forming and machining of materials, components and products. As tooling costs often represent a substantial fraction of manufacturing costs (Scheffer et al. 2003), their reduction represents a strong profitability lever. Tools usually consist of different components, which differ by their tool wear. Components of milling tools, for example, can be divided into arbor, shell and milling cutter. Whereas tool life of the former component type is relatively high and wear is relatively low compared to its usage, wear of the latter is much higher and inasmuch needs to be replaced more frequently (Bouzakis et al. 2009). Hence, different tool component types n need to be considered separately. Comparable tool component types i, however, are exposed to similar wear and enable the production of similar quantity of units, until the tool component needs to be replaced. Therefore, an average quantity of units $\overline{x_{tT}}$ producible with the same tool component type i [see Eq. (12.11)] is considered.

$$C_{\mathrm{t}} = \sum_{i=1}^{n} \bar{c}_{\mathrm{t},i} \cdot x_{\mathrm{t},i} = \sum_{i=1}^{n} c_{\mathrm{T},i} \cdot \frac{\overline{x_{\mathrm{t},i}}}{\overline{x_{\mathrm{tT},i}}} \cdot \frac{n_{\mathrm{pv}}}{\overline{n_{\mathrm{tT},i}}}, \tag{12.11}$$

C_{t} total tooling costs,
n number of different tool component types,
$\bar{c}_{\mathrm{t},i}$ average costs per piece of tool component type I,
$x_{\mathrm{t},i}$ quantity of tool component types i consumed over lifetime,
$c_{\mathrm{T},i}$ costs for tool component type i,
$\overline{x_{\mathrm{t},i}}$ average quantity of units, which shall be produced with the tool component type i,
$\overline{x_{\mathrm{tT},i}}$ average quantity of units producible with the tool component type i until replacement,
n_{pv} number of product variants,
$\overline{n_{\mathrm{tT},i}}$ average number of variants producible with tool component type i,

In case of external procurement of tools, tool cost reduction can only be influenced by the quantity of tool components consumed x_{t}. On the one hand, the consumption of tool components is influenced by the number of product variants n_{pv} divided by the average number of variants producible per component type $\overline{n_{\mathrm{tT},i}}$. For example, the production of variants with diverse product shapes may require different milling heads. Through modular product systems the average number of variants producible per tool component can be increased. On the other hand, the number of necessary tool components depends on the tool component life, which ends as soon as the targeted product quality cannot be realized anymore due to tool wear (Cook 1973).

Thus, each tool component lasts only for an average quantity of unit $\overline{x_i}$ and needs to be replaced after that. The tool life heavily depends on the physical, chemical and thermal influence during machining. For instance, high force intensity leads to stronger wear on tools (Altintas 2012).

Material Costs

Material costs depend on the material price c_{m} per mass, masses of the different materials of a product variant $m_{\mathrm{c},i}$, mass of the cutoffs m_{o}, rejection rates r, quantities of units x as well as a learning rate b, see Eq. (12.12).

Wright discovered in 1936 that material costs decrease with increasing quantity due to less waste and discounts for larger quantities. Due to these learning effects in material utilization and process quality as well as sales discounts, integrating a learning rate b is suggested. Owing to this learning effect, all variables in Eq. (12.12) relate to the first product produced. These cost factors are exemplary depicted in the following.

The manufacturing technology determines the choice of material and therefore influences the material costs c_{m}. Advanced technologies eventually can use cheaper materials and thus reduce material costs. For instance, self-optimizing assembly of laser systems does not demand high-quality lenses, since the assembly process compensates losses in lens quality (see Chap. 10). In contrast, advanced technologies can also require relatively high-priced materials compared to materials for conventional processes. One example is the high price of powder for additive manufacturing, which needs to be compensated for, to some extent, by less material consumption.

Here, optimal product designs and structures help to reduce the mass of the product materials m_{c} by simultaneously maintaining the product's functionality (see Chap. 2). Virtual testing of materials can help pinpoint the optimal material consumption and avoid the over-engineering of products (see Chap. 5).

The mass of cutoffs m_{o} and therefore material waste is predetermined both by the chosen manufacturing technology and the optimal material utilization. Additive manufacturing technologies, for instance, completely avoid cutoffs compared to cutting processes.

Finally, rejection rates r_{ij}—which are specific consumed materials or entire products that do not satisfy the quality requirements and hence not processed any further—can be minimized by optimizing the production process. Process control, like avoidance of machine vibrations, can prevent errors during the process and thus reduce rejection rates (see Chap. 9).

$$C_{\mathrm{m}} = \sum_{j=1}^{n_{\mathrm{pv}}} \sum_{i=1}^{n_{\mathrm{m}}} c_{\mathrm{m},ij} \cdot \rho_{ij} \cdot \left(V_{\mathrm{c},ij} + V_{\mathrm{o},ij}\right) \cdot \frac{1}{\left(1 - r_{ij}\right)} \cdot x_j^{1-b}, \tag{12.12}$$

C_{m} total material costs,
n_{pv} number of product variants,
n_{m} number of different materials for product variant j,
$c_{\mathrm{m},ij}$ unit price for material i and product variant j,
ρ_{ij} density of material i for product variant j,
$V_{\mathrm{c},ij}$ required volume of material i for product variant j,
$V_{\mathrm{o},ij}$ volume of cutoff of material i and product variant j,
r_{ij} rejection rate of material i and product variant j; with $0 \leq r_{ij} < 1$ and $r_{ij} \in \mathbb{R}$,
x_j quantity of units of product variant j,
b learning rate; with $0 < b \leq 1,\ \ b \in \mathbb{R}$.

12.5 Conclusion

The profitability assessment of new manufacturing technologies in this book was conducted with the aim to draft a starting point for a technology-oriented theory of production. At the beginning, a literature review on production theories reflecting the state-of-the-art in research highlighted the research gaps. In this context, it was recognized that the interest in production theory research has significantly decreased over the past decades and calls for a revival. Hence, the majority of extant theories focus on a pure economic view of the value chain and treat manufacturing processes as a 'black box' instead of combining specific technological and economic relationships in the productive transformation of input to output. Consequently, there is a lack of applicability leading to an increasing gap between current production functions on the one hand and modern production technologies on the other. Against this backdrop—and in an effort to refuel the academic discussion on production theory—this book aims to contribute in two major ways:

First, the relevance of modern production technologies in the transformation of goods is grounded in their economic impact by means of functions in the form of a profitability assessment. For this purpose, the production technologies of the four Cluster of Excellence domains—*Individualized Production Systems, Virtual Production Systems, Integrated Technologies,* and *Self-Optimizing Production Systems*—were examined. The impact of these cluster technologies on sales, fixed and variable costs was derived bottom-up by individually identifying each technology's primary and secondary technological drivers (e.g., unit time) and translating them into economic variables of profitability (e.g., labor costs). The resulting equations were characterized as hypotheses and are thus to be understood as an indicative framework for the subsequent quantification of effects. In sum, focus was therefore primarily put on an economic assessment, which may be further complemented with ecological and social factors.

Second, the technology-oriented theory of production provides an illustrative framework for linking the profitability impact of modern production technologies to the four commonly distinguished competitive priorities of manufacturing firms (i.e., cost, quality, flexibility, and delivery performance) and the polylemma of production (i.e., the scale-scope and plan-value dichotomies). In this context, it is reasoned that the involved relationships are no longer to be seen as mutually exclusive, but instead may be largely resolved by means of technological and managerial advances. Consequently, the theory may provide guidance for managers to cope with these seemingly dichotomous relationships, thereby further increasing the competitiveness of manufacturing companies in high-wage countries.

To conclude, the technology-oriented theory of production aims at integrating technological and economic relationships enabling the assessment of production technologies. In this way, it supports decision-makers in aligning their firm's competitive priorities with investments in advanced manufacturing technologies. It is thus not to be understood as a holistic general production theory—but rather as a new partial theory integrating aspects of modern production technologies and management.

The resulting limitations provide fruitful avenues for further research. Involving ecological and social aspects could provide a new lens on the discussed production technologies and may represent a step towards an integrative theory. In addition, it is an ongoing effort to empirically test the outlined hypotheses and interdependencies (e.g., in the form of quantifications based on industry cases) on a broader basis. Finally, future research should revert to the state of understanding production theory as a living phenomenon that requires continuous improvement to enhance its applicability. Scholars may build upon and continuously add to the technological and economic drivers (with its corresponding equations) outlined in this book in order to provide further guidance to manufacturing firms in high-wage countries on how best to align their competitive priorities.

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