Application and validation of a holistic profitability model within the technology-oriented theory of production

Günther Schuh
Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University

Malte Brettel
Chair of Business Administration for Engineers and Natural Scientists - Center for Entrepreneurship, RWTH Aachen University

Jan-Philipp Prote
Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University

Sebastian Schloesser
s.schloesser@wzl.rwth-aachen.de
Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University

Stefan Pöhler
Chair of Business Administration for Engineers and Natural Scientists - Center for Entrepreneurship, RWTH Aachen University

Frederick Sauermann
Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University

Thomas Kießling
Chair of Business Administration for Engineers and Natural Scientists - Center for Entrepreneurship, RWTH Aachen University

Julian Kress
j.kress@wzl.rwth-aachen.de
Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University

Abstract

In the course of significant and rapid technological and managerial progress in various domains of the manufacturing industry, individual advances with respect to a company's profitability have hardly been assessable for years. At this, the development of a technology-oriented theory of production is meant to facilitate an indication of how technological and managerial advances contribute to solve major trade-offs in the context of industrial manufacturing and how this affects the overall profitability.

For that reason, an outline of a comprehensive formula-based theory of production is applied to an industrial uses case of production planning and control in this paper.

Keywords: Theory of production, trade-off theory, production planning and control

Introduction

Competition in manufacturing industries recently intensified while at the same time new machinery, tools, infrastructure, and know-how emerged from technological progress. In parallel the popularity of production theory research, measuring the impact of technological progress on a company's overall profitability, significantly decreased over the last decades (Schuh et al., 2017). One of the main reasons is that research has mainly focused on explaining specific fields of production technologies rather than operationalizing production systems holistically (Nyhuis and Wiendahl, 2010). Research on production theory so far aims at describing the process of transforming input to output goods in a quantitative matter (Dyckhoff, 2006) and thereby encounters important shortcomings (Nyhuis and Wiendahl, 2010).

To address these shortcomings, a technology-oriented theory of production is developed. First, the theory extends focus beyond production and includes indirect processes. Second, technological and managerial advances are considered to facilitate an assessment of their profitability implications. Third, besides costs, also quality, delivery performance, and flexibility are captured. These four measures open different dichotomous relationships and determine manufacturing companies' strategic direction and competitiveness (Schmenner and Swink, 1998; Ward, McCreery, Ritzman, and Sharma, 1998). The opposing relationship between costs and flexibility form the first inherent trade-off in manufacturing companies. The second one is manifested by the counteracting relationship between process flexibility and delivery performance. (Schuh, Potente, and Hauptvogel, 2014). These trade-offs constitute the polylemma of production, which represents several general conflicts within manufacturing companies (Schuh et al., 2017). This paper aims at answering the question "How can technological advancements in the field of manufacturing help to solve the dichotomous relationships in the polylemma of production?" The concept of a technology-oriented theory of production has been developed in an interdisciplinary research cluster. It consists of four technological domains (ICDs), which are additive manufacturing, virtual production, self-optimized production and integrated technologies (Schuh, Potente & Hauptvogel, 2014). Driven by a cross-domain research group, the theory of production has been elaborated, investigating the respective technological, processual and performance characteristics of individual domains. In a three-stage approach, an individual profitability metric for each domain has been defined by elaborating an individual, generalizable set of production formulas. In a further step, research findings were validated in a real-time environment, leveraging proprietary manufacturing environments. In this paper, it is exemplarily outlined, how the validation of the profitability model was rolled-out in the context of production planning and control.

Related work

Production functions serve as quantitative relationships between input and outputs of production units (Krelle, 1969). Turgot (1766), with his classic s-shaped production function for agriculture, and Cobb and Douglas (1928), with their neo-classic production function for industrial manufacturing, both offered early forms of production theories.

Both suggest a substitutional relationship of input factors. This paper refers to these theories as type A production functions (Schuh et al., 2017).
Responding to several critics on substitutional relationships, Leontief (1951) proposed a limitational relationship among input factors. Similarly, Gutenberg (1973) challenged the neo-classical approach. Incorporating important aspects of Leontief's function, he developed a business-oriented function that considers related management activities and differentiates usage and consumption input factors (Dyckhoff, 2006; Fandel, 2005). Various researchers expanded this so-called type B production function (Steven & Blank, 2013) by including the different steps of production processes (Heinen, 1983), their substitutability (Kloock, 1969), interdependencies (Küpper, 1996) and additional firm conditions (Matthes, 1996).

Against the background of these different theories and functions, the technology-oriented theory of production, being subject of this research, shall be delineated. For this purpose, extant literature has been analysed to derive a set of distinct characteristics which can be used to classify the described types of production functions across five dimensions.

First, the primary object of analysis has been either focused on the description and derivation of mathematical functions (Corsten, 2012; Fandel, 2005; Matthes, 1996) or, in addition, on the understanding and decomposition of processes which determine in- and outputs (Dyckhoff, 2006; Koopmans, 1951). The technology-oriented theory of production is positioned to constitute a process-oriented theory because it helps to evaluate the benefits of different combinations of in- and outputs by means of a decomposition of properties and processes of specific production technologies (Schuh et al., 2017).

Second, and in contrast to other production functions such as types A to F which exclusively rely on deterministic input-output relationships (Gutenberg, 1973; Heinen, 1983; Schwalbach, 2014), the technology-oriented theory of production strives to also incorporate cybernetic relationships (Beer, 1985; Dyckhoff, 2006). In this regard, Dyckhoff's (2006) cybernetic models serve as a valid basis, allowing to examine self-optimizing production systems, for example - a core area of research within the described ICDs (Brettel et al., 2016; Schuh et al., 2017).

Third, and in line with more recent theories of production, i.e., type E and F (Schwalbach, 2014), dynamic time-effects are considered in the conceptualization. For instance, self-optimizing production systems are expected to exhibit socio-technical learning curves which can be realized in the short-run (Brettel et al., 2016) and account for product life cycles with a time-to-market perspective in the long-run (Schuh et al., 2017).

Fourth, the technology-oriented theory of production is thought to describe multi-product firms which are characterized by the manufacturing of several product variants in a firm. In contrast to theories focusing on settings in which only one primary product by means of certain input factors are produced (Dyckhoff, 2006), it is not only aimed at being able to account for several but rather an infinite number of product variants in the theory. Accordingly, it is argues that the consideration of an infinite-product environment will become particularly relevant in assessing economic benefits of new production technologies such as selective laser melting (Schuh et al., 2017).

Fifth, and most importantly, the technology-oriented theory of production does not rely on a purely economic focus which is usually associated with cost and production data on an aggregated level but, instead, has a strong technological focus (Schuh et al., 2017). That is, the theory is built upon profound engineering knowledge (e.g., fluid mechanics) and thus incorporates natural scientific laws (Schuh et al., 2017). In this respect, functions can be taken from the field of engineering production functions (Chenery, 1949;

Ferguson, 1950). However, the overall theoretical framework is also based on economic factors which serve as a guiding structure to enable the profitability assessment of different production technologies (Schuh et al., 2017).

Conceptual model

As initially stated, it is aimed at contributing to explain how operations managers and researchers can balance the existing trade-offs between a manufacturing firm's four operational capabilities (Schuh et al., 2017). That is cost, quality, flexibility and delivery performance (Boyer & Lewis, 2002; Olhager, 1993; Swamidass & Newell, 1987). At its heart, the conceptual model thus builds on trade-off theory (Boyer & Lewis, 2002) which is reflected in the previously mentioned "polylemma of production". Trade-off theory suggests that firms are facing significant tensions between competing capabilities and competitive priorities which cannot be fully resolved and thus remain (Boyer & Lewis, 2002; Boyer, Swink & Rosenzweig, 2005).

While acknowledging the existence and necessity of trade-offs, this stream of literature is advanced by positing that the depicted dichotomous relationships can be shifted by means of technological advances. This view is thus in contrast to the traditional approach which considered trade-offs as constraints that cannot be eliminated and lead to the necessity to concentrate on the achievement of a limited set of goals and tasks (Hayes & Schmenner, 1978; Skinner, 1974). Another contrasting view propagated the idea that competitive priorities might be rather complementary than mutually exclusive and thus could be achieved simultaneously (Collins & Schmenner, 1993; da Silveira, 2005; Schonberger, 1986). Authors also suggested that the improvement of trade-offs might follow a specific sequence (da Silveira, 2005). Ferdows and De Mayer (1990), for instance, proposed a "sandcone model" starting from quality and moving on to dependability, flexibility and cost. Finally, Hayes and Pisano (1996) integrated these perspectives by introducing the idea of performance or asset frontiers to trade-off management. The technology-oriented theory of production builds on this integrated view. In line with da Silveira (2005), it is therefore argued that advances in technology can enable firms to move from inferior to superior frontiers thereby shifting dichotomous relationships to an enhanced level of performance as compared to the existing frontier.

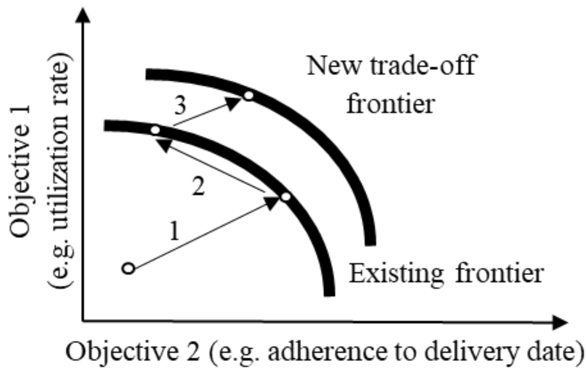

Figure 1 - Trade-Off Frontiers and Decisions. Adapted from da Silveira, 2005.

Figure 1 summarizes the three key decisions to address trade-offs (da Silveira, 2005): (1) optimization, (2) repositioning, and (3) enhancement. If plants are not running at the optimal configuration with their current asset bases, performance can be increased by means of optimization. Once, the existing performance frontier is reached, dichotomous relationships can only be optimized by repositioning configurations along the frontier so that an improvement in objective 1 is improved at the expense of objective 2. However, advances in technology can partly resolve trade-offs by shifting them towards a new, superior frontier which leads to an increase in both objectives (da Silveira, 2005).

Building on the delineation of the technology-oriented theory of production across the different dimensions above, the conceptual model is specified as follows (Schuh et al., 2017): First, production systems are perceived to constitute complex and socio-technical environments which cannot be fully predicted but can be rather explained by assuming dynamic, multi-product settings with cybernetic aspects. Accordingly, it is strived to explain the factors of quality, flexibility, and delivery performance by taking reference to and incorporating the Kano model of quality (Kano et al., 1984), product variants, and time-to-market in the model. Second, the cost focus of prior theories of production is acknowledged so that the factor of cost is explained by considering product engineering as well as manufacturing functions in the model. This includes product and tool development costs, material costs, machine hourly rates and labor costs.

As a result, the following overall, basic equation which operationalizes technological advances at an aggregate level in terms of their impact on profitability is derived (eq. 1). Furthermore, the price function of production theory, which depends on the product and service quality, is illustrated (eq. 2).

Equation (1):

$$Profit = Sales - Fixed\ Costs - Variable\ Costs$$

$$= \underbrace{p_q \cdot x_{sv}}_{Sales} - \underbrace{\sum_{j=1}^{n} C_j}_{Fixed\ Costs} - \underbrace{\left[t_u \cdot (c_{mh} + c_l) + C_t + C_m\right] \cdot x_{pv}}_{Variable\ Costs}$$

x_{sv}:	*units sold of all product variants*	t_u:	*unit time*
x_{pv}:	*units produced of all product variants*	c_{mh}:	*machine hourly rate*
n:	*number of activities*	c_l:	*labor costs per hour*
p_q:	*price depending on the product and service quality*	C_t:	*tooling costs*
		C_m:	*material costs*
C_j:	*fixed costs of one block/ activity j (e.g., product development)*		

Equation (2):

$$p_q = p_0 \cdot \underbrace{\left[1 + \left(e_{b,p} \cdot \pi_p + e_{b,s} \cdot \pi_s\right)\right]}_{\text{Price basis due to basic expectations}} \cdot \underbrace{\left\{1 + \left[\left(e_{s,p} + e_{d,p}\right) \cdot \pi_p + \left(e_{s,s} + e_{d,s}\right) \cdot \pi_s\right]\right\}}_{\text{Price premium due to satisfiers and delighters}}$$

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* $\pi_s, \pi_p \in R$

$e_{b,i}$: *customer satisfaction due to fulfillment of basic expectations; with* $-1 \leq e_{b,i} \leq 0$ *and* $e_{b,i} \in R$

$e_{s,i}$: *customer satisfaction due to fulfillment of satisfiers; with* $e_{s,i} \geq 0$ *and* $e_{s,i} \in R$

$e_{d,i}$: *customer satisfaction due to fulfillment of delighters; with* $e_{d,i} \geq 0$ *and* $e_{d,i} \in R$

For being able to assess the benefits of specific technologies, this equation is thought to serve as a starting point for further detailing relevant technological variables (e.g., number of forming steps, main time for primary shaping) influencing profitability in terms of their impact on sales and cost. For the purpose of exemplification and validation, the application of the theoretical framework to an industrial use case from the field of production planning and control is described in the following section.

Application and validation of production theory in production control

The theory of production aims at answering how technological and managerial advances contribute to solve the dichotomous relationships in the polylemma of production. Therefore, the technology-oriented theory of production is developed in an interdisciplinary research cluster. Within a cross-sectional process (CSP), the respective technological, processual and performance characteristics of the ICDs are investigated. The theory of production is manifested in a set of formulas, which are derived from an overall profitability formula. Targeting at a comprehensive validation of the overall theory, the formulas were applied to the different technological domains. Based on several workshops with experts from the different domains, the impact of technological and managerial advances within an ICD to a company's profitability was evaluated qualitatively. In a second step, the theory of production was taken to quantify these impacts. In this paper the technological domain of self-optimizing production planning and control (ICD D1) is taken as an example to explain the methodology of validation. Furthermore, insights from the application of the theory of production are reflected in this paper.

ICD D1 focuses on the enhancement and configuration of production planning and control with respect to individual production locations. According to Lödding (2008), production planning and control comprises four general tasks: order generation, order release, capacity control and sequencing. In this context, short throughput time, low stock, high adherence to delivery date, and high utilization rate frame the fundamental logistic targets (Lödding, 2008; Schuh et al., 2014). From these targets, inherent trade-offs emerge which the manufacturing industry has been facing for years (Nyhuis & Wiendahl, 2012). For example, utilization rate and adherence to delivery date are competing targets, resulting in a specific trade-off.

According to the previously introduced trade-off theory, production planning and control configurations can be identified, which optimize both utilization rate and adherence to delivery date simultaneously, until a certain operating frontier is reached. In this context, the operating frontier represents the maximum performance level production planning and control can achieve by utilizing the current setup of technological and managerial manufacturing infrastructure. Therefore, production planning and control configurations target at an optimal balance between the conflicting targets with respect to the company's strategy. A low utilization rate usually allows for a flexible assignment of manufacturing resources to production orders, enabling a strong adherence to delivery dates. On the other hand, a high utilization rate usually provokes shortages at any of the various manufacturing resources which leads to a weaker level of adherence to delivery dates. Taking the overall profitability equation (eq. 1) as well as the equation for product prices (eq. 2) into account, the opposing effects of the mentioned trade-off can transparently be quantified. While a higher utilization rate results in a lower machine hourly rate (Brinker et al., 1989), the reduced level of delivery time adherence results in a decrease of service quality, being especially negatively perceived by industrial customers (Coghlan & Coughlan, 2003). At this, the achievable price and even the number of sellable units nowadays decreases with the level of delivery time adherence in the majority of manufacturing industry sectors (Coghlan & Coughlan, 2003).

As mentioned above, the operating frontier represents the maximum performance level that a technological domain can achieve by utilizing the current infrastructural setup. In the context of production planning and control this setup is understood as a company's capability of managing the major tasks of production planning and control order generation, order release, capacity control and sequencing as outlined above. Due to the structural inflexibility of production systems, variations between production planning and control configurations are rather incremental since any structural change of a running production systems induces costly efforts. This fact already constitutes the operating frontier of conventional production planning and control. Furthermore, the complexity of production planning and control easily reaches human cognitive limitations, leading to performance limitations of production planning and control configurations.

Facing these circumstances, ICD D1 focuses on the enhancement of production planning and control configurations by introducing algorithmic solving of multidimensional optimization problems. This way, various configurations of production planning and control are generated, simulated and evaluated with respect to the above mentioned logistic targets.

At a German manufacturer of different large-scale serial components for the automotive industry, the optimization of production planning and control configurations has challenged production planning departments for years. Especially the increasing product and process variety has turned the task of order and sequence planning into a substantial challenge over the past years (Schuh & Stich, 2012).

Conventional approaches of optimizing production planning and control have led the company to an operating frontier, comprising certain performance levels in work in progress, utilization rate, throughput time and adherence to delivery date as shown in figure 2 (solid line). The illustrated production planning and control configuration represented the optimal achievable compromise between the performance levels of the individual logistic targets with respect to the overall company's strategy for years. However, competition in the automotive supplier industry has increasingly necessitated stronger adherence to delivery dates, since automotive OEMs (Original Equipment Manufacturer) request just-in-time delivery and barely accept delays in component delivery. In the same course, the German component manufacturer has to keep a strong adherence to delivery dates as a key service value proposition to justify a price premium compared to foreign competitors.

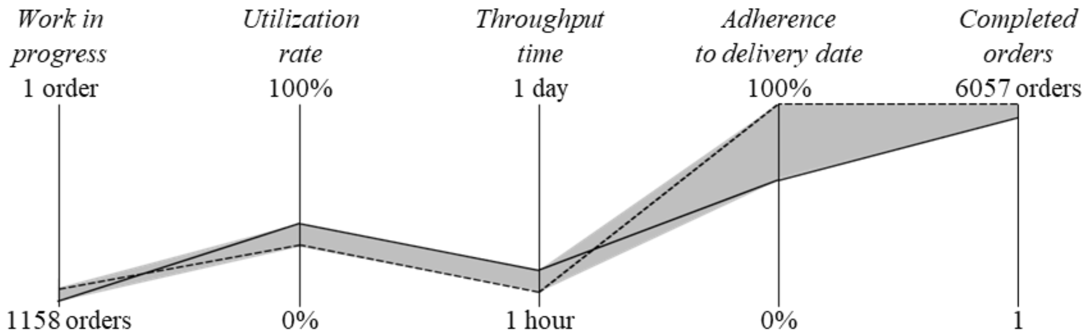

Figure 2 – Performance level configuration of production planning and control

Since conventional planning approaches have reached an operating frontier, the company has applied a simulative optimization approach in cooperation with ICD D1. Based on existing production data, which has been generated over years, the simulation of various configurations of production planning and control was facilitated. Even substantial changes in the production system such as additional production capacity or new sequences of manufacturing steps, which can hardly be considered for a valid assessment in conventional planning approaches due to structural inflexibility, have been investigated in simulation. Based on algorithmic solving of a multidimensional production planning and control optimization problem, ICD D1 revealed additional configurations, from which an optimum is illustrated in figure 2 (dotted line).

In this case, the adherence to delivery date, which has been identified as one of the most critical value propositions in the automotive supplier industry, significantly improved by up to 30% compared to an optimum that has been identified based on a conventional planning approach. In the same course, drawbacks by about 5% in the performance level of utilization rate and throughput time have nearly been neglectable.

The implementation of simulation-based production planning and control constitutes a major technological and managerial improvement, not only for the mentioned German component manufacturer, but for many companies, pursuing data-based production models in the context of Industrie 4.0 (Schlick et al., 2014). Similar to other technological and managerial advances, the impacts of suchlike improvements on the overall profitability of a manufacturing company has hardly been assessable for years. At this, the formula-based theory of production serves as suitable framework to quantify these impacts.

Starting from an overall profitability equation (eq. 1), the parameters, affected by technological or managerial advances can be identified. In the example of simulation-based production planning and control (ICD D1) it can be assumed, that mainly *Sales Price* and *Variable Costs* are affected. Table 1 illustrates, how the parameters of the detailed equations for *Variable Costs* and *Sales Price* are affected in this case.

Table 1 – Impact of production planning and control configuration on key parameters

Variable Costs (eq. 1)		*Sales Price (eq. 2)*	
Parameter	Impact	Parameter	Impact
t_u	main process time (const.) auxiliary process time (+)	$e_{s,i}$	$e_{s,s}$ (++) $e_{s,p}$ (const.)
c_{mh}	(+)	$e_{d,i}$	$e_{d,s}$ (++) $e_{d,p}$ (const.)
c_l	const.		
C_t	const.	π_i	const.
C_m	const.	$i = s$	
x_{pv}	const.	$i = p$	

The unit time as a parameter of the *Variable Costs* is slightly affected due to an increased auxiliary process time. In the same course, the production processes itself as well as the associated main process times are assumed to stay constant. In the context of a slightly decreased level of utilization rate, the machine hourly rate increases.

Regarding the *Sales Price* it is assumed, that the level of adherence to delivery dates hardly affects the price basis but mainly is represented by a significant price premium, especially being achievable in the context of large-scale serial components for the automotive industry. Moreover, product performance indicators are usually assumed to not be impacted when adapting production planning and control configurations.

This way, the theory of production operationalizes technological and managerial advances at an aggregate level in terms of their impact on a company's profitability. In the illustrated example of simulation-based production planning and control, the theory of production facilitates a quantitative identification of the economically optimal operating point. This is to be seen as the point, when positive effects of higher adherence to delivery dates overcompensate the inherent drawbacks of lower utilization rate and higher throughput time. Consequently, the theory of production serves as a valid tool to make the impacts of different production control configurations on the overall profitability tangible.

Conclusion and further research

The formula-based theory of production has been validated as a valid tool to quantify advances in different technological domains with respect to the impact on a company's profitability. The set of equations is to be seen generally applicable to various technological domains but still requires specific knowledge in interpreting and applying the different parameters according to the context of a technological domain. Based on the theory of production, further research will focus on applying the equations to further technological domains to validate and to continuously refine the set of equations. Furthermore, the theory of production enables the elaboration of quantitative production models to facilitate automated analytics. For industrial practice the theory of production serves as a comprehensive framework to initially assess the impact of technological and managerial advances on the overall profitability. This way, the framework serves as a decision-making support in manufacturing infrastructure investments.

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