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Discussion Paper

An Optimization Model for Valuating Process Flexibility

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Completed Research Paper

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Abstract

Although flexible processes are deemed critical for many companies and constitute a key concern of business process management, there is a lack of approaches for valuating process flexibility from an economic perspective and for determining an appropriate level of process flexibility. Today, companies do not know how flexible their processes should be. While generally advocating balanced investments, scholars provide concrete recommendations for very specific settings only. What is missing is a more general guidance and a deeper investigation of the positive economic effects of flexible processes, which are hard-to-measure and beset with risks. Against this backdrop, we propose an optimization model that enables determining the optimal level of process flexibility in line with the principles of value-based business process management. We also report on the insights gained from applying the optimization model to the production processes of an international company from the semi-conductor industry.

Keywords: Business Process Management, Process Flexibility, Optimization Model, Decision Analysis, Value-based Management

Introduction

W. Edwards Deming, a pioneer of quality management and business process improvement, once said: *"It is not necessary to change. Survival is not mandatory."* In a world where many companies face strong competition, flexibility becomes a more and more desired capability (Weber et al. 2008). In particular, flexible processes are critical to cope with increasing requests for individualized treatment and escalating levels of demand uncertainty (Goyal and Netessine 2011; Gong and Janssen 2010; Schonenberg et al. 2008). Decreasing time-to-market and time-to-customer-demands are further drivers that make process flexibility to a key concern of today's business process management (BPM) (Rosemann et al. 2008; van der Aalst 2013). More flexible processes, however, are not necessarily better (He et al. 2011). Rather, the appropriate level of process flexibility depends on the business environment and the internal condition of a process as well as on the related positive and negative economic effects (Neuhuber et al. 2013; van Biesebroeck 2007). As determining the economic value of flexible processes is a challenging task for scholars and practitioners alike, further research in this area is worthwhile (Schober and Gebauer 2008).

Despite its importance, there is little research dedicated to the economic valuation of process flexibility. Only lately, quantitative models have been proposed. Braunwarth et al. (2010), for instance, present an optimization model that helps insurance companies determine whether claims should be handled in a highly automated and standardized manner or in a more flexible way by involving human operators. The model relies on the expected present value of the short-time cash effects for executing the process and for settling claims as well as the long-term effects of customer satisfaction. Braunwarth and Ullrich (2010) propose a model that supports service providers in deciding whether process instances should be executed in-house or routed to an external service provider depending on the workload. Neuhuber et al. (2013) estimate the optimal levels of volume and functional flexibility for service processes as a foundation for selecting flexibility projects. While their model considers positive effects of process flexibility, it is based on a single period and deterministic cash flow only. Extending their own prior work, Schober and Gebauer (2008) present a real options-based model for valuating information systems flexibility while considering uncertainty, variability as well as time-criticality as properties of the involved processes. They take on a stochastic perspective in order not to underestimate the value of flexibility. Nevertheless, they only cover the cost effects of flexibility. He et al. (2011) provide a model that identifies the need for flexibility within a process with respect to demand variation and correlation. Although their flexibility fit index highlights where flexibility needs to be increased, it does not consider the economic effects of process flexibility.

Based on this review of related work, we can extract the following three challenges that research dedicated to the economic valuation of process flexibility has to address: (1) Current models focus on processes from a particular application domain or on information systems in general. What is missing is a model that abstracts from domain peculiarities and provides more general guidance. (2) Most models focus on how flexibility reduces costs. Approaches that consider positive economic effects of process flexibility model them either in a coarse-grained and hard-to-measure way or neglect their stochastic and long-term nature. (3) Process flexibility usually refers to a single process as unit of analysis. Additional benefits that may arise from extending the scope of process flexibility to multiple processes have not been explored yet. All these challenges lead to the following research question: *How flexible should the processes of a company be if positive economic effects of process flexibility receive particular attention and if process flexibility is considered as a concept that relates to multiple processes?*

To address the challenges and to answer the research question, we propose an optimization model that determines the optimal level of process flexibility with respect to an objective function that complies with the principles of value-based BPM. Such an approach is reasonable as process design decisions should be informed by analytical calculations from the operations management field (vom Brocke et al. 2011) and because value-based BPM is an established paradigm for process decision-making (Bolsinger et al. 2011; Buhl et al. 2011). The optimization model considers two processes, one with an inferior and the other with a superior output. By maximizing the risk-adjusted expected present value of cash inflows and outflows, the model determines how flexible the process with the inferior output should be to cover the risky demand of the process with the superior output. Roughly, process flexibility refers to those capacity units that can be reallocated from the process with the inferior output to the process with the superior output. Our model meets the challenges outlined above, as it (1) applies to all processes whose output is sold to customers, (2) considers positive economic effects of process flexibility (e.g., by including increased cash inflows from selling more superior outputs, a risky demand, and a multi-period planning horizon), and (3) interprets process flexibility as a concept that applies to two processes.

The remainder of the paper is structured as follows: First, we outline the theoretical background with respect to process flexibility and value-based BPM that is necessary to understand the optimization model. We then present the optimization model and report on the insights gained from applying the model to the production processes of an international company from the semi-conductor industry. We conclude by discussing limitations and pointing to topics for future research.

Theoretical Background

Foundations of Process Flexibility

When developing an optimization model for the economic valuation of process flexibility, we need to consider how flexibility in general and process flexibility in particular are defined, how process flexibility can be implemented, and what characteristics drive process flexibility.

Though being researched for decades, flexibility is a not fully developed and immature concept (Chanopas et al. 2006; Mandelbaum and Buzacott 1990; Saleh et al. 2009). The "vagueness of the term" (Upton 1995, p. 205) resulted in a plethora of definitions, which several scholars tried to compile and structure (de Toni and Tochia 1998; Oke 2005; Saleh et al. 2009). Sethi and Sethi (1990), for instance, report on more than fifty definitions alone from the manufacturing domain. There are both very general definitions that do not allow for a concrete measurement (Mascarenhas 1981; Regev and Wegmann 2005; Zelenoic 1982) and highly specific definitions that exclusively focus on a single facet of flexibility (Bordoloi et al. 1999; Johnston and Clark 2005). Further, flexibility refers to distinct objects (e.g., processes, infrastructure, or information systems) and types (e.g., strategic, operational). We define flexibility as "the capability of a system to react to or to anticipate system or environmental changes by adapting its structure and/or its behavior considering given objectives" (Wagner et al. 2011a, p. 811).

In this paper, we focus on process flexibility on an operational level. We define process flexibility using a slightly adapted version of Goyal and Netessine's (2011) definition of product flexibility. This analogy is reasonable as processes also intend to create value-added output (Dumas et al. 2013; Hammer 2010). We focus on core processes, which are also known as business processes or operational processes, whose output is eventually sold to customers (Harmon 2010). That is, we cover both manufacturing processes that create products like cars and service processes that provide services like cloud storage or appraisals of credit-worthiness. Product flexibility is "the ability to manufacture multiple products on the same capacity, and the ability to reallocate capacity between products in response to realized demand" (Goyal and Netessine 2011, p. 180). In the view of Goyal and Netessine, product flexibility equals mix flexibility, product mix flexibility, and particularly process flexibility. Although product flexibility is usually treated as a sub-category of manufacturing flexibility, our model is not restricted to the manufacturing domain. This leads to the following definition of process flexibility: *"Process flexibility is the ability to create multiple outputs on the same capacity, and to reallocate capacity between processes in response to realized demand."*

Process flexibility, as defined here, is a hybrid form of volume flexibility and functional flexibility because it allows processes to cope with risky demand and to create different outputs. Volume flexibility enables to "profitably increase or decrease production above and below the installed capacity" (Goyal and Netessine 2011, p. 182). Functional flexibility enables responding to increasing output variety and refers to "the readiness with which the tasks performed […] can be changed in response to varying business demands" (Sethi and Sethi 1990, p. 293). In line with our definition of process flexibility, it is appropriate to use a broader understanding of process that also includes the resources and people involved during process execution. This understanding is in line with the definition of a work system, which is "a system in which human participants and/or machines perform work (processes and activities) using information, technology, and other resources to produce products/services for specific internal and/or external customers" (Alter 2013, p. 75).

As for the implementation of process flexibility, it is worthwhile to take a look at volume and functional flexibility with a focus on ideas that have been proposed for their implementation. Volume flexibility has been mainly researched from a capacity management and revenue management perspective (Fitzsimmons and Fitzsimmons 2011). While revenue management focuses on how to favorably influence demand, capacity management deals with the supply side (Sasser 1976). Moreover, volume flexibility has been subject to several empirical studies (Jack and Raturi 2002; Suarez et al. 1996). Examples for projects related to the implementation of volume flexibility are the expansion of inventory buffers or the introduction of overtime or extra shifts (Jack and Raturi 2002; Slack 1983).

Functional flexibility has a rich tradition in BPM. From a conceptual perspective, Schonenberg et al. (2008) proposed a framework of four strategies that relate to functional flexibility, namely flexibility-by-design, flexibility-by-deviation, flexibility-by-underspecification, and flexibility-by-change. The strategies enable processes to react to changes in a way that does not require substantial redesign. While flexibility-by-design allows a process to choose among predefined execution paths, flexibility-by-deviation allows temporarily adapting a process at run time. In case of high uncertainty where processes require loose specifications, flexibility-by-underspecification allows for completing a process specification at run time. Flexibility-by-change enables to cope with events that cannot be addressed by temporary deviations. While the strategies proposed by Schonenberg et al. (2008) are widely accepted, process flexibility has also been picked up by some other authors in a similar manner. Kumar and Narasipuram (2006), for example, distinguish between the possibility to implement various pre-defined process steps and the possibility to postpone the design to the moment when flexibility is needed. From a more technical perspective, the literature related to process-aware information systems, workflow management, and business process design proposed numerous ideas for implementing the conceptual ideas sketched above (Agostini and De Michelis 2000; Heinl et al. 1999; Rosemann and Recker 2006; van der Aalst 2013). These ideas include, among many others, configurable process models, adaptation and redesign patterns, exception handling, the selection of suitable fragments from a process repository, and approaches to process versioning as well as instance migration (Kaan et al. 2006; Reichert and Weber 2012). On the level of resources and people, exemplary ideas for implementing functional flexibility are cross-training or flexible machines (Iravani et al. 2005).

As for the characteristics that drive process flexibility, the literature provides several classifications. In their work about information system flexibility, Gebauer and Schober (2006) characterize a process in terms of time-criticality, variability, and uncertainty. Time-criticality represents the percentage of time-critical tasks in a process. Variability measures how frequently and with which concentration different variants of process tasks are performed. Uncertainty splits into environmental and structural uncertainty. Environmental uncertainty refers to dynamic changes in the process environment and therefore to external factors and their predictability. In the context of our model, environmental uncertainty relates to the uncertain demand for process outputs. Structural uncertainty, in contrast, deals with uncertainty within the process. Uncertainty is also a driver for process flexibility in the model of He et al. (2011), who introduce demand variation and demand correlation as main drivers of process flexibility. In the area of supply chain management, Pujawan (2004) determines internal and external drivers of process flexibility. For example, he introduces product variety and process similarity. Product variety is about the number of different products a process produces. Process similarity is considered high if different products pass through many similar processes with similar machine tools and process times. Reichert and Weber (2011) present a taxonomy of factors that determine the need for flexible processes supported by a process-aware information system. These factors are variability, looseness in the sense of uncertainty about the process steps before execution, adaption, and evolution. In addition, Wagner et al. (2011b) present eight factors that drive process flexibility. These factors include, for example, the cycle time of a process and the time between planning and execution. By means of their eight factors, Wagner et al. (2011b) are able to categorize whether a process has a high, medium, or a low need for flexibility. Another categorization authored by Huth et al. (2001) divides processes in exclusive, complex, and short-lived processes on the one hand and well-known, standardized processes on the other hand. The first process type requires high levels of flexibility, whereas the second process type requires low levels of flexibility. As can be seen, there is a variety of characteristics that drive process flexibility. In our optimization model, we use some of these characteristics to operationalize the cash effects.

Value-based Business Process Management

When determining the optimal level of process flexibility, the related positive and negative effects have to be valuated from an economic perspective. In this paper, we rely on value-based BPM for deriving a well-founded objective function for the optimization model. Value-based BPM is a paradigm where all process-related activities and decisions are valued according to their contribution to the company value. That is, value-based BPM applies the principles from value-based management to process decision-making. Therefore, we briefly elaborate on the foundations of value-based management (see also Buhl et al. 2011).

Value-based management, as a substantiation and extension of the shareholder value concept, sets the maximizing of the long-term, sustainable company value as the primary objective for all business activities (Koller et al. 1990; Martin et al. 2009). The fundament of value-based management is the work of Rappaport (1986), Copeland et al. (1990), and Stewart and Stern (1991). The company value is determined based on future cash flows (Rappaport 1986). Value-based management can only be claimed to be implemented if all activities and decisions on all management levels align with the objective of maximizing company value. Therefore, companies must not only be able to quantify the company value on the aggregate level, but also the value contribution of individual activities or decisions. Decisions that comply with value-based management must be based on cash flows, consider risks, and incorporate the time value of money (Buhl et al. 2011).

There is a set of objective functions that are used for value-based decision-making (Buhl et al. 2011). The appropriateness of different objective functions depends on the decision situation at hand and the risk attitude of the decision makers. In case of certainty, decisions can be based on the net present value of the future cash flows (Martin et al. 2009). In case of risk with risk-neutral decision makers, decisions can be made based on the expected net present value. If decision makers are risk-averse, decision alternatives can be valuated using the certainty equivalent method or a risk-adjusted interest rate (Berger 2010). Intending to capture the uncertainties of the positive effects related to process flexibility, the optimization model is based on an expected present value with a risk-adjusted interest rate for discounting.

Optimization Model

Basic Idea

The optimization model considers two processes that are operated by a single company. One process produces an inferior output with a low profit margin, the other process a superior output with a high profit margin. Each process faces a risky demand and has a specific capacity, which indicates the maximal amount of outputs the process is able to produce in a single period of time. In line with the theoretical background, process flexibility means that capacity can be reallocated. Considering the differences in the profit margin, we allow capacity to be reallocated from the process with the inferior output to the process with the superior output. That is, the process with the inferior output provides capacity for producing the superior output. The process with the superior output, in contrast, receives capacity. Thus, we also refer to the process with the inferior output as providing process and to the process with the superior output as receiving process.

From an economic perspective, process flexibility impacts both cash inflows and outflows. Additional cash inflows can be realized if the demand for the superior output exceeds the capacity of the receiving process. In this case, it is reasonable to increase the capacity of the receiving process by reallocating capacity from the providing process. Such a reallocation reduces the capacity of the providing process and may lead to a capacity shortage that makes it impossible to fully serve the demand for the inferior output. In this case, the cash inflows from selling the inferior output decrease. Cash outflows result from implementing flexibility projects such as those sketched in the theoretical background. Thus, there is a trade-off between the cash inflows and the cash outflows, which we resolve with our optimization model.

Below, we first introduce central assumptions and the objective function. We then substantiate the objective function by modeling how process flexibility impacts cash inflows and outflows. Finally, we solve the optimization model and analytically determine the optimal level of process flexibility.

Assumptions and Objective Function

The demand for each process output $X_{\mathrm{sup/inf}} \in \mathbb{R}_0^+$ is assumed to be uniformly distributed. In addition, the capacity of each process $C_{\mathrm{sup/inf}} \in \mathbb{R}^+$ is set to the expected value of the respective demand distribution (He et al. 2011). The demand for a process output therefore symmetrically scatters around the process capacity with a deviation $D_{\mathrm{sup/inf}} \in \mathbb{R}^+$, and ranges from a minimum demand (e.g., $C_{\mathrm{sup}} - D_{\mathrm{sup}}$) to a maximum demand (e.g., $C_{\mathrm{sup}} + D_{\mathrm{sup}}$). All realizations in this interval are equally probable. The uniform distribution with symmetric deviations was chosen to ensure that the optimization model can be solved analytically. Although the optimization results depend on the concrete distribution, other symmetric distributions such as the normal distribution do not change the results fundamentally. The demand for both process outputs was furthermore assumed to be independent from each other. This requires the company to consider systematic dependencies already when setting the process capacities before applying the optimization model (Zhang et al. 2003). Finally, the demand for the inferior output is assumed to be independent and identically distributed over all periods under investigation. The same holds true for the periodic demand for the superior output. On this foundation, we construct a multi-period model while capturing the fact that investments in process flexibility yield positive effects over several periods.

Assumption 1: The demand for the inferior and the superior process output is uniformly distributed and scatters symmetrically around the capacity of the providing and the receiving process, respectively. The demand for the inferior output is independent from the demand for the superior output. The periodic demands for the inferior as well as for the superior outputs are independent and identically distributed.

With flexibility being our main focus, the next step is to define flexibility technically and how it affects the capacity of the receiving process. As process flexibility enables to support other processes by reallocating capacity, we quantify process flexibility as that percentage of the capacity units of the providing process that can be used to produce the superior output of the receiving process. We distinguish between the flexibility potential $F \in [0; 1]$, which is the level of flexibility established at the beginning of the multi-period planning horizon, and the realized flexibility $f \in [0; F]$, which is the level of flexibility used in each period. The flexibility potential is the maximal level of flexibility that can be used. Thus, it constitutes an upper boundary for the realized flexibility. From a conceptual point of view, there are two decisions to be made: an investment decision concerning the flexibility potential at the beginning of the planning horizon, and an execution decision concerning the level of flexibility realized in each period. Henceforth, we use the notions flexibility potential and flexibility as synonyms. The technical definition of process flexibility enables modeling the additional capacity of the receiving process based on the flexibility and the capacity of the providing process. To transform the provided capacity into the additional capacity, we use an exchange rate $T \in \mathbb{R}^{+}$. The exchange rate indicates how many units of the superior output can be produced by reallocating one capacity unit of the providing process. It depends on the characteristics of both processes and their outputs, and thus needs to be determined outside the model. An example of how to determine the exchange rate is shown in the application section. Taking the technical definition of process flexibility and the exchange rate, the additional capacity for the superior output is $F \cdot C_{\mathrm{inf}} \cdot T$.

To valuate process flexibility from an economic perspective, we need the profit margins of each process output $M_{\mathrm{sup/inf}} \in \mathbb{R}^{+}$. We assume the profit margins to be constant over time and the amount of outputs sold. This approach is known as cost-plus-pricing, which means that a company has a fixed margin that is added to the production costs in order to obtain the sales price (Arrow 1962). The practical relevance of cost-plus-pricing corroborates the assumption of constant profit margins (Guilding et al. 2005). As a result, additional sales volume of the superior output can be directly transformed into additional cash inflows. Likewise, capacity shortages of the inferior output can be translated into reduced cash inflows.

Assumption 2: The profit margins are constant over time and over the sold amount of outputs.

Finally, the objective function of the optimization model needs to be specified. As shown in the theoretical background, the principles of value-based management are adopted to an ever higher extent in the field of process decision-making. Therefore, the model aims at maximizing the risk-adjusted expected value of the cash effects that go along with investing in process flexibility. The objective function equals the difference of the risk-adjusted expected present value of the cash inflows $I(F)$ and the cash outflows $C(F)$.

$$\text{MAX: } I(F) - C(F) \tag{1}$$

Cash Inflow Effects of Process Flexibility

The cash inflow effects of process flexibility are obtained by analyzing the expected increases in the cash inflows from selling the superior output $p(F)$ and the expected decreases in the cash inflows from selling the inferior output $o(F)$. We therefore investigate the stochastic implied by the optimization model and the structure of different demand realizations (see the decision tree in Figure 1).

The top-most layer of the decision tree from Figure 1 indicates whether process flexibility creates cash inflows depending on the demand for the superior output. If the capacity of the receiving process is sufficient to cover the demand for the superior output, it is not necessary to reallocate capacity. The implemented flexibility will not be used and does not create cash inflows (case 1). As this case is irrelevant for flexibility considerations, it is omitted from the further analysis. If the capacity of the receiving process is too small for covering the demand for the superior output, capacity needs to be reallocated (case 2). This is why we explore this case in more detail. Case 1 and case 2 occur with a probability of 0.5 each, because the demand scatters symmetrically around the capacity (see *Assumption 1)*. The middle layer of the decision tree focuses on the demand for the inferior output. The amount by which the cash inflows from selling the inferior output is reduced depends on the level of process flexibility and on the realized demand levels of both outputs. If the demand for the inferior output exceeds the capacity of the providing process, a capacity shortage will definitely occur and reduce the cash inflows that result from selling the inferior output (case 2.1). If the demand for the inferior output is smaller than the capacity of the providing process, the providing process has free capacity that can be used for reallocation (case 2.2). In this case, it is not certain whether capacity reallocation leads to a reduction in the cash inflows from the inferior output. Therefore, this case has to be analyzed in more detail. Analogous to cases 1 and 2, case 2.1 and case 2.2 occur with a probability of 0.5 each. The bottom-most layer of the decision tree analyzes whether the highest capacity reallocation enabled by a distinct level of flexibility potential can be entirely covered by the free capacity of the providing process. Remember that a distinct level of flexibility potential and the demand realization for the superior output determine how many capacity units of the providing process have to be reallocated. Moreover, the providing process has a minimum demand. If the remaining capacity, i.e., the capacity that remains with the providing process after a reallocation, is able to cover the minimum demand of the providing process for the highest possible reallocation, the required amount of reallocated capacity may be exclusively served by free capacity (Case 2.2.2). If the capacity of the providing process can be reduced that much that the remaining capacity gets smaller than the minimum demand, the required amount of reallocated capacity may not be exclusively served by free capacity (Case 2.2.1). Both cases 2.2.1 and 2.2.2 require a different modeling. They depend on the relation between the chosen level of flexibility potential and a distinct threshold that is based on the capacity of the providing process and the demand deviation of the inferior output. We provide more details below.

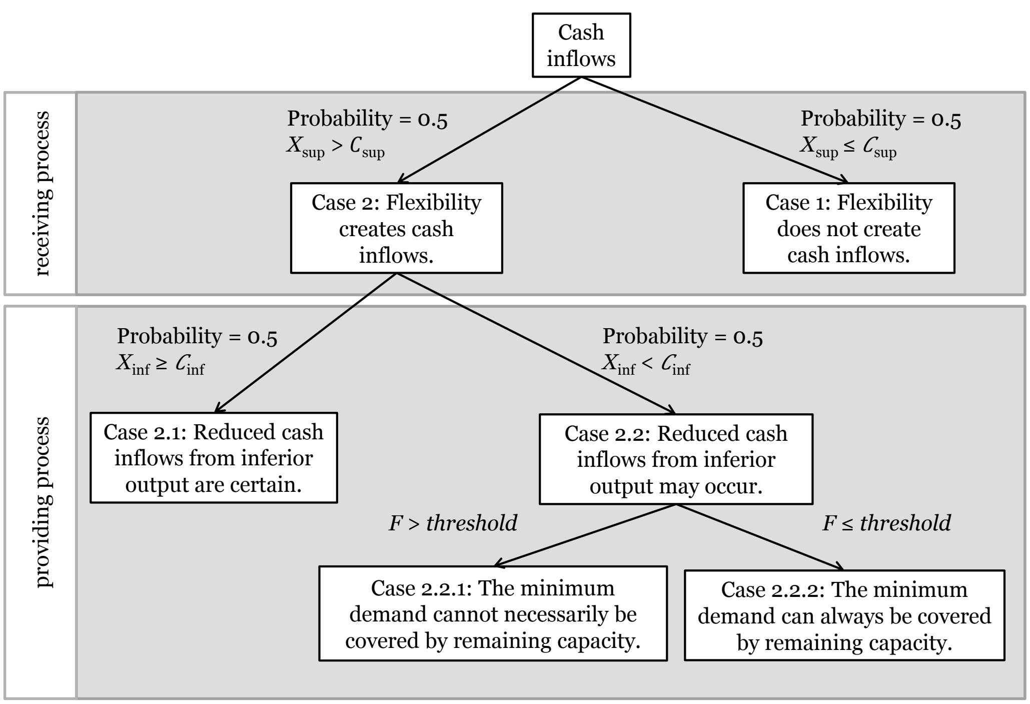


Figure 1. Decision tree for determining the cash inflows

Increased Cash Inflows from Selling More Superior Outputs

First of all, we derive the expected increases in the cash inflows from selling more superior products given a distinct level of process flexibility. This corresponds to case 2 from Figure 1. The cash inflow increases depend on the excess demand for the superior product. The excess demand ranges from 0, if the demand for the superior output is smaller than or equals the capacity of the receiving process, to D_{sup}, if the demand for the superior output realizes at the maximum demand. Due to the reproduction property of the uniform distribution, the excess demand is uniformly distributed in the interval $[0, D_{\text{sup}}]$. To obtain the amount of process flexibility that is necessary to cover a given excess demand, the excess demand has to be divided by $C_{\text{inf}} \cdot T$. The division by T transforms the excess demand into required capacity units of the providing process. The division by C_{inf} leads to the related percentage of the capacity of the providing process. Depending on the uncertain demand, the realized flexibility f is a random variable, too. It is uniformly distributed on the interval $[0; \frac{D_{\text{sup}}}{C_{\text{inf}} \cdot T}]$ with the density function $u(f) = \frac{C_{\text{inf}} \cdot T}{D_{\text{sup}}}$ (Berger 2010).

For a distinct level of realized flexibility f, the cash inflow increases are obtained by multiplying the flexibility with $C_{\text{inf}} \cdot T$ to get the additional sales volume of the superior output and by multiplying the additional sales volume with the profit margin of the superior output M_{sup}. The corresponding profit function is $p(f) = f \cdot C_{\text{inf}} \cdot T \cdot M_{\text{sup}}$. One has to consider that not all excess demand realizations can be covered because the flexibility potential F constitutes an upper boundary. Larger excess demands lead to a complete realization of the flexibility potential and to the corresponding cash inflows. They do not lead to cash inflows beyond. Formula (2) shows the expected increases in the cash inflows from selling more superior outputs. The integral in the first addend relates to the demand realizations that can be covered. The second addend deals with the demand realizations that cannot be covered completely.

$$E[p(f)] = \int_0^F f C_{\text{inf}} T M_{\text{sup}} \cdot u(f) df + \left(1 - \frac{F C_{\text{inf}} T}{D_{\text{sup}}}\right) \cdot C_{\text{inf}} T M_{\text{sup}} F = M_{\text{sup}} C_{\text{inf}} T F - \frac{M_{\text{sup}} {C_{\text{inf}}}^2 T^2}{2 D_{\text{sup}}} \cdot F^2 \qquad (2)$$

Reduced Cash Inflows from Selling Less Inferior Outputs

To derive the reduced cash inflows from selling less inferior outputs, we have to consider both the demand distribution of the superior output and the inferior output. The reduced cash inflows result from the fact that less units of the inferior output can be sold as (parts of) the capacity of the providing process is used for producing the superior product of the receiving process. This corresponds to the cases 2.1 and 2.2 from Figure 1. Exemplary illustrations for the cases 2.1, 2.2.1, and 2.2.2 are shown in Figure 2.

In case 2.1, the demand for the inferior output exceeds the capacity of the providing process. As, due to the reallocation, the capacity of the providing process is reduced at the same time, the remaining capacity is always smaller than the realized demand. This leads to a capacity shortage and to reduced cash inflows. For a distinct level of realized flexibility f, an amount of $f \cdot C_{\text{inf}}$ capacity units needs to be reallocated. The corresponding loss function is $o(f) = f \cdot C_{\text{inf}} \cdot M_{\text{inf}}$. To derive the expected decreases in the cash inflows, the loss function has to be integrated over the density function $u(f)$ of the realized flexibility, which we defined in the section above. Analogous to case 2, the highest decreases in cash inflows are determined by the chosen level of flexibility potential F. That is why formula (3) is identically structured as formula (2).

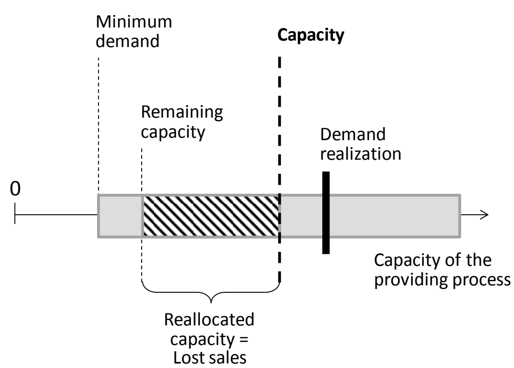
$$E_{2.1}[o(f)] = \int_0^F f C_{\text{inf}} M_{\text{inf}} \cdot u(f) df + \left(1 - \frac{F C_{\text{inf}} T}{D_{\text{sup}}}\right) \cdot F C_{\text{inf}} M_{\text{inf}} = M_{\text{inf}} C_{\text{inf}} F - \frac{M_{\text{inf}} {C_{\text{inf}}}^2 T}{2 D_{\text{sup}}} \cdot F^2 \qquad (3)$$

In case 2.2, the demand for the inferior output is smaller than the capacity of the providing process. As a consequence, the providing process disposes of free capacity that can be reallocated without leading to a capacity shortage regarding the inferior output. The free capacity $k \in \mathbb{R}_0^+$ equals the difference between the demand realized for the inferior output and the capacity of the providing process. As the free capacity is 0, if the demand for the inferior output equals the capacity of the providing process, and D_{inf}, if the demand realizes at the minimum demand, it follows a uniform distribution on the interval $[0; D_{\text{inf}}]$ with the density function $u(k) = \frac{1}{D_{\text{inf}}}$.

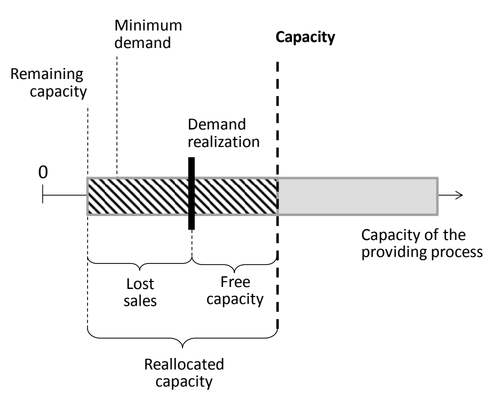
As already mentioned above, a distinct level of realized flexibility results in reallocated capacity of $f \cdot C_{\text{inf}}$. If the reallocated capacity is smaller than the free capacity of the providing process, the excess demand for the superior output can be exclusively covered by free capacity units. In this case, no decreases in the cash inflows occur. If the reallocated capacity exceeds the free capacity of the providing process, there is a capacity shortage regarding the inferior product. In this case, the cash inflows decrease. The loss in sales volume of the inferior output given a specific realization of free capacity equals the difference between the reallocated capacity and the free capacity, i.e., $(fC_{\text{inf}} - k)$. The expected loss in sales volume equals the integral of the difference just described over the density function of the free capacity. As only realizations between 0 and $f \cdot C_{\text{inf}}$ are relevant, the integral is parameterized with these values. To obtain the expected decreases in cash flows for a distinct level of realized flexibility $E_{2.2}[o(f)]$, the expected loss in sales volume must be multiplied by the profit margin of the inferior output:

$$E_{2.2}[o(f)] = \int_0^{f \cdot C_{\text{inf}}} (fC_{\text{inf}} - k) \cdot M_{\text{inf}} \cdot u(k)dk = f^2 \cdot \frac{{C_{\text{inf}}}^2 M_{\text{inf}}}{D_{\text{inf}}} - f^2 \cdot \frac{{C_{\text{inf}}}^2 M_{\text{inf}}}{2D_{\text{inf}}} = f^2 \cdot \frac{{C_{\text{inf}}}^2 M_{\text{inf}}}{2D_{\text{inf}}} \qquad (4)$$

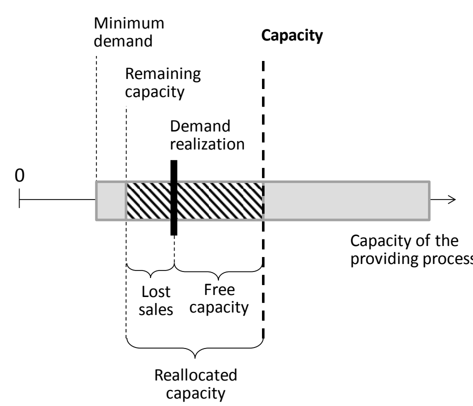
In order to fully specify the reduced cash inflows, an additional case distinction is necessary that relates to the cases 2.2.1 and 2.2.2 from Figure 1. If the level of flexibility potential F exceeds $\frac{D_{\text{inf}}}{C_{\text{inf}}}$, the reallocated capacity $f \cdot C_{\text{inf}}$ may exceed the demand deviation D_{inf}. Furthermore, if we consider that the free capacity cannot be higher than D_{inf}, it becomes evident that it may not be possible that the reallocated capacity can be covered by free capacity only. Otherwise, the reallocated capacity may be exclusively covered by free capacity. Therefore, the threshold mentioned in Figure 1 is $\frac{D_{\text{inf}}}{C_{\text{inf}}}$.



Case 2.1: Reduced cash inflows from inferior output are certain.



Case 2.2.1: The minimum demand cannot necessarily be covered by remaining capacity.



Case 2.2.2: The minimum demand can always be covered by remaining capacity.

Figure 2. Exemplary illustration for the cases 2.1, 2.2.1, and 2.2.2

In case 2.2.2, we analyze those levels of the realized flexibility that are smaller than or equal the threshold. To obtain the expected decreases in cash inflows, the function $E_{2.2}[o(f)]$ is integrated over the density function of the process flexibility. This covers all excess demand realizations for the superior output that can be covered by the chosen level of process flexibility. Again, larger realizations are considered as well.

$$E_{2.2.2}[O(f)] = \int_0^F E_{2.2}[o(f)] \cdot u(f)df + \left(1 - \frac{FC_{\text{inf}}T}{D_{\text{sup}}}\right) \cdot E_{2.2}[o(f)] = F^2 \cdot \frac{{C_{\text{inf}}}^2 M_{\text{inf}}}{2D_{\text{inf}}} - F^3 \cdot \frac{{C_{\text{inf}}}^3 T M_{\text{inf}}}{3D_{\text{inf}}\, D_{\text{sup}}} \tag{5}$$

In case 2.2.1, we analyze those levels of realized flexibility that exceed the threshold. In this case, the expected decreases in cash inflows result from combing the formulas derived so far. For flexibility realizations smaller than the threshold, the decreased cash inflows are uncertain and function (5) can be applied. For flexibility realizations larger than the threshold, formula (3) can be used because in this case reduced cash inflows are certain as well. In both cases, further realizations are directly transformed into decreased cash inflows. The only difference is an adjustment of free capacity that does not occur in the first case. The expected free capacity for these realizations equals $\frac{D_{\text{inf}}}{2}$. For these capacity units, the cash inflows do not decrease. In terms of expected values, the decreased cash inflows are certain after an adjustment of $\frac{D_{\text{inf}}}{2} \cdot M_{\text{inf}}$ to account for free capacity units. Therefore, the expected decreases in cash inflows for levels of process flexibility larger than $\frac{D_{\text{inf}}}{C_{\text{inf}}}$ equal:

$$E_{2.2.1}[O(f)] = \int_0^{\frac{D_{\text{inf}}}{C_{\text{inf}}}} f^2 \cdot \frac{{C_{\text{inf}}}^2 M_{\text{inf}}}{2D_{\text{inf}}} \cdot u(f)\,df + \int_{\frac{D_{\text{inf}}}{C_{\text{inf}}}}^F \left(fC_{inf}M_{inf} - \frac{D_{\text{inf}}}{2} \cdot M_{\text{inf}}\right) \cdot u(f)df + \left(1 - \frac{FC_{\text{inf}}T}{D_{\text{sup}}}\right) \cdot \left(FC_{\text{inf}}M_{\text{inf}} - \frac{D_{inf}}{2} \cdot M_{\text{inf}}\right) = -\frac{D_{\text{inf}}}{2} \cdot M_{\text{inf}} + \frac{D_{\text{inf}}^2}{6\,D_{\text{sup}}} \cdot M_{\text{inf}}T + M_{\text{inf}}C_{\text{inf}}F - \frac{M_{\text{inf}}{C_{\text{inf}}}^2 T}{2D_{\text{sup}}} \cdot F^2 \tag{6}$$

Finally, to get the overall cash inflow effects of process flexibility for a single period, the intermediate results obtained so far have to be combined by weighting them with their corresponding probability from the decision tree shown in Figure 1.

$$I_{\text{period}}(F) = \frac{M_{\text{sup}}C_{\text{inf}}T}{2} \cdot F - \frac{M_{\text{sup}}{C_{\text{inf}}}^2 T^2}{4D_{\text{sup}}} \cdot F^2 - \begin{bmatrix} \frac{{C_{\text{inf}}}^2 M_{\text{inf}}}{8D_{\text{inf}}} \cdot F^2 - \frac{{C_{\text{inf}}}^3 T M_{\text{inf}}}{12D_{\text{inf}}\, D_{\text{sup}}} \cdot F^3 + \frac{M_{\text{inf}}C_{\text{inf}}}{4} \cdot F - \frac{M_{\text{inf}}{C_{\text{inf}}}^2 T}{8D_{\text{sup}}} \cdot F^2 & \text{for } F \le \frac{D_{\text{inf}}}{C_{\text{inf}}} \\ -\frac{D_{\text{inf}}}{8} \cdot M_{\text{inf}} + \frac{D_{\text{inf}}^2}{24\,D_{\text{sup}}} \cdot M_{\text{inf}}T + \frac{M_{\text{inf}}C_{\text{inf}}}{2} \cdot F - \frac{M_{\text{inf}}{C_{\text{inf}}}^2 T}{4D_{\text{sup}}} \cdot F^2 & \text{for } F > \frac{D_{\text{inf}}}{C_{\text{inf}}} \end{bmatrix} \tag{7}$$

The periodic cash inflow function is continuous and monotonically increasing with decreasing marginal inflows[1].

Cash Outflow Effects of Process Flexibility

Up to now, only the cash inflow effects of process flexibility have been considered. This would result in 100 % process flexibility since the superior output has a much higher profit margin than the inferior output. However, making processes more flexible also leads to cash outflows. Cash outflows do not only depend on the level of process flexibility, but also on other factors: (a) cash outflows for project overhead such as for administration and coordination, and (b) process-related characteristics such as the criticality of certain process steps and the similarity of two processes.

First of all, process flexibility itself is analyzed. The idea of enabling a process to flexibly use its capacity is in line with the concept of flexibility-by-design (Schonenberg et al. 2008). Flexibility-by-design requires that various execution alternatives – in our case producing the own output or the output of the receiving process – have to be enabled. In line with our broad understanding of processes, process flexibility further requires that the resources and people of the organization are flexible (Sethi and Sethi 1990). The higher the desired level of process flexibility, the more flexibility projects are to be implemented. Implementing more flexibility projects also leads to cash outflows for administration and coordination, which are known to increase over-proportionally with the project size (Verhoef 2002). In addition, a company is likely to implement the cheapest flexibility projects first. We model the properties of the cash outflows using the function $F^2 \cdot C_{\text{inf}}$. As one can see, the outflows increase with the desired level of process flexibility and capture the project overhead as the level of process flexibility is raised by the power of two. Of course, any

[1] The explicit proof for these properties can be requested from the authors.

larger exponent would fulfill the requirement of an over-proportional course as well. We chose to use a squared function because this keeps the already complex optimization problem analytically solvable, an approach inspired by Goyal and Netessine (2011). As for monetization, the cash outflows needed to make one capacity unit of the providing process flexible, i.e., to enable the production of T superior outputs, have to be incorporated. This factor highly depends on the processes at hand. In a worst-case scenario, the receiving process has to be duplicated and included in the providing process to enable the production of the superior output on the providing process. Although this worst case would most likely lead to prohibitively high cash outflows and correspondingly to an optimal level of process flexibility of zero, it is a reasonable starting point to estimate the cash outflows. Duplicating the receiving process would lead to cash outflows that equal the initial investment for implementing the receiving process. It would also enable the production of C_{sup} superior outputs. By dividing these cash outflows by the capacity of the providing process and the exchange rate, we get the highest possible outflows for making one capacity unit of the providing process flexible. The corresponding parameter is called scaling factor $G \in \mathbb{R}^+$. The cash outflows that occur in the worst case scenario for a distinct level of process flexibility are $C_{\text{inf}} \cdot F^2 \cdot G$.

When estimating the actual cash outflows for a distinct level of process flexibility, we use process-related characteristics to reduce the cash outflows of the respective worst-case scenario. Obviously, only those process steps that limit the capacity of the receiving process have to be incorporated in the providing process. We call these process steps critical. The more critical steps the receiving process has, the more process steps have to be supported by the providing process and the more expensive is the establishment of a distinct level of process flexibility. Therefore, the first process-related characteristic that reduces the scaling factor is criticality. The criticality is inspired by the ideas from Gebauer and Schober (2006), and is defined as the relation between the number of all process steps and the number of critical process steps of the receiving process:

$$\frac{\sum \text{critical steps of the receiving process}}{\text{all steps of the receiving process}} \quad (8)$$

The next process-related characteristic is how many critical process steps are similar in the providing and the receiving processes. The more similar the providing and the receiving process are, the less cash outflows occur for establishing a distinct level of process flexibility. Therefore, the similarity s (with $0 \leq s \leq 1$) between a critical process step of the receiving process and its counterpart in the providing process also reduces the worst-case cash outflows. For the further analysis, only the similarity between *critical* process steps matter as all other process steps have already been taken out by criticality. To present an approach to determining similarity, we refer to the concept of variability introduced by Gebauer and Schober (2006). They use the concept of the Lorenz curve to derive the concentration of process variants (i.e., different execution paths of a process). The higher the concentration of the process variants, the lower is the need for process flexibility. As Gebauer and Schober focus on one process instead of two, this concept has to be adjusted to consistently fit into our model. We therefore use the frequency distribution of the variants of the receiving process to determine to what extent a critical process step of the receiving process is already supported by its counterpart in the providing process. Consider that a critical process step i has n_i different variants $v_{i,j}$. The variants of this process step occur with a frequency $p(v_{i,j}) \in [0,1]$. To obtain the similarity, we introduce a decision variable $d(v_{i,j}) \in \{0,1\}$ that equals 0 if the variant $v_{i,j}$ of the critical process step i can only be produced by the providing process after a flexibility investment and equals 1 if the variant can already be produced. The decision variables are weighted with the occurrence frequency of the corresponding variant and cumulated over the variants n_i. The result is a frequency-weighted average of the similarity of the support for the critical process step i:

$$s_i = \sum_{j=1}^{n_i} p(v_{i,j}) \cdot d(v_{i,j}) \quad (9)$$

When multiplying the criticality measure with the scaling factor we get an estimate for the cash outflows by implicitly assuming that each process steps is equally expensive to install. This estimate, however, does not consider that similar process steps do not create outflows. By subtracting the similarity measure from 1, we get a standardized variable that reflects the non-similarity of a critical process step, a quantity that is responsible for cash outflows. Summing up these non-similarity measures over all critical process steps weights the critical process steps with their similarity and, thus, is a reasonable estimate for adjusting the scaling factor. In the following, we use the process factor r that adjusts the scaling factor not only for non-critical process steps, but that also incorporates the processes' similarity.

$$r = \frac{\sum_{i \in \text{critical process steps}} (1-s_i)}{\text{all steps of the receiving process}} \tag{10}$$

By multiplying the process factor and the scaling factor, the cash outflows for making a single capacity unit of the providing process flexible can be estimated as the scaling factor, defined as the worst-case outflows for a given level of process flexibility, is adjusted based on the process characteristics that naturally support process flexibility. To obtain an estimate for the final cash outflows, the product of the process factor and the scaling factor has to be multiplied with $C_{\text{inf}} \cdot F^2$.

$$C(F) = \quad C_{\text{inf}} \cdot F^2 \cdot G \cdot r \tag{11}$$

Solving the Optimization Model

To find the optimal level of process flexibility, we calculate the risk-adjusted expected present value of the cash effects. As the cash outflows occur as an initial investment at the beginning of the planning horizon, no discounting is necessary to obtain the present value. The present value of the expected cash inflows can be derived by discounting the periodic cash inflows. For many investment periods, the discounting can be approximated by the perpetuity. Following the concept of the perpetuity, the expected cash inflows per period is divided by the risk-adjusted interest rate $i > 0$. The optimum of the objective function is characterized by the equality of the marginal cash inflows and the marginal cash outflows. As the marginal cash outflows are strictly increasing and strictly convex and as the marginal cash inflows are strictly decreasing, there is exactly one optimum, i.e., a global maximum. It has also to be taken into account that there are different objective functions due to the two cases of the cash inflow function (see formula 7). Whether the optimum is located in the first or in the second definition range cannot be forecast without knowing concrete values for the model parameters. Thus, two optimality conditions must be derived.

$$F^* = \frac{\frac{C_{\text{inf}} M_{\text{inf}}}{D_{\text{inf}}} + \frac{2 M_{\text{sup}} C_{\text{inf}} T^2}{D_{\text{sup}}} + 8Gri - \frac{M_{\text{inf}} C_{\text{inf}} T}{D_{\text{sup}}} - \sqrt{\left(-\frac{C_{\text{inf}} M_{\text{inf}}}{D_{\text{inf}}} - \frac{2 M_{\text{sup}} C_{\text{inf}} T^2}{D_{\text{sup}}} - 8Gri + \frac{M_{\text{inf}} C_{\text{inf}} T}{D_{\text{sup}}}\right)^2 - \frac{4 C_{\text{inf}}^2 T M_{\text{inf}}}{D_{\text{inf}} D_{\text{sup}}} \cdot (2 M_{\text{sup}} T - M_{\text{inf}})}}{\frac{2 C_{\text{inf}}^2 T M_{\text{inf}}}{D_{\text{inf}} D_{\text{sup}}}} \quad \text{for } F \leq \frac{D_{\text{inf}}}{C_{\text{inf}}} \tag{12a}$$

$$F^* = \frac{(M_{\text{sup}} T - M_{\text{inf}})}{\frac{C_{\text{inf}} T}{D_{\text{sup}}} \cdot (M_{\text{sup}} T - M_{\text{inf}}) + 4Gri} \text{ for } F > \frac{D_{\text{inf}}}{C_{\text{inf}}} \tag{12b}$$

Real-World Application

To demonstrate how the optimization model can be used in practice, we report on the insights gained from applying the model to the production processes of a company from the semi-conductor industry. As the model can be applied to different kinds of processes, the production process case is only one example.

We first provide some background information about the context of the case company and the concrete case, then challenge an already made investment in process flexibility, and finally determine the optimal level of process flexibility based on the optimization model. Owing to confidentiality, the identity of the case company will not be disclosed. Moreover, all data had to be anonymized and slightly modified. However, the principal results still hold.

As typical for the semi-conductor industry, the case company has a predisposition for investing in process flexibility. This is because it has to cope with short product lifecycles, highly fluctuating demand, and huge investments in a very competitive environment (Teramoto et al. 2012). Our contact point with the case company was the management of the strategic production planning department. This department is in charge of all decisions affecting the company's production processes, which includes decisions on process flexibility and capacity. The management provided us with an investment case from one of their factories in South Asia. Applying the optimization model to this case revealed useful insights particularly into how the model may have to be adapted, how the parameters can be operationalized, and how necessary real-world data can be collected. The application also pointed to limitations and topics for further research. The interaction with the case company was as follows: We presented our model and developed a catalogue of questions that were answered by our contact person in the course of a two-hour interview. After having finished the model development phase, the manager provided us with the case at hand, which has been compiled in close collaboration with the volume planning department. To clarify open questions and collect data, we conducted a second interview. As we already were in close communication with a manager from the strategic production planning department during the development of our model, we could include selected industry requirements already at an early stage of research.

The investment case is as follows: The case company had the opportunity to invest in a new machine to increase the flexibility of its production process for super junction metal-oxide-semiconductor field-effect transistors (SMOSFET). The SMOSFET is used for example in LCD and LED displays as well as for lighting solutions. Note that, in the case at hand, the process output does not refer to a single transistor, but to a wafer with multiple transistors. To simplify the production process of a SMOSFET wafer, we focus on two process steps, namely the production of the metal layer (ML) and the production of the photo layer (PhL). One SMOSFET wafer requires 12 PhL and 2 ML. The second production process creates a more advanced product, which is a mix of a SMOSFET and a bipolar junction transistor (BJT), henceforth called SM-BJT. For example, the SM-BJT is used in the automobile sector. To produce one SM-BJT wafer, 24 PhL and 3 ML are required. In addition to the two steps of the SMOSFET process, the SM-BJT process requires a third step where a special PhL is produced. This step needs to be executed 3 times per SM-BJT wafer. The special PhL can be produced by the new machine only. As SMOSFET is the inferior output and SM-BJT is the superior output, the SMOSFET process is the providing process and the SM-BJT process is the receiving process. One important aspect of this case is that in contrast to our model the capacity of the SM-BJT process, i.e., the receiving process, is zero. Consequently, the top-most layer of Figure 1 does not exist, a circumstance that makes the question whether the receiving process has enough capacity obsolete.

When applying the optimization model, we require specific data to estimate the parameters. As for the cash inflows, we need the exchange rate, the margin and the demand deviation of both outputs as well as the capacity of the SMOSFET process. To calculate the exchange rate, we had to consider the properties of both processes. In the case at hand, the ML production is the only limiting process step. Only 2,000 ML can be produced per week, which corresponds to a process capacity of $C_{\text{inf}} = 1{,}000$ SMOSFET per week. The exchange rate $T = 0{,}67$ results from dividing the 2 necessary ML need for SMOSFET through the 3 ML needed for SM-BJT. When calculating the margins, it is important to know that, in the semi-conductor industry, the margin of a wafer is calculated based on the amount of PhL it includes. The margin is 27.2 EUR per PhL of a SMOSFET and 32 EUR per PhL of an SM-BJT. By multiplying the margin with the amount of PhL, we get the margin per wafer, which is $M_{\text{inf}} = 326.4$ EUR for SMOSFET. For SM-BJT, the margin is $M_{\text{sup}} = 896$ EUR per wafer. It is calculated by multiplying the margin per PhL with the sum of both types of PhL included, i.e., the standard layers that are also used for SMOSFET and the special layers. The demand deviation was said to follow a normal distribution, which indicates that assuming a uniform distribution simplifies reality. Our contact person provided us with the expected demand and the standard deviation of both outputs. The expected demand for SMOSFET amounted to 1,000 wafers per week. The corresponding production capacity had the same value as the case company also sets the process capacity to the expected demand. The relative standard deviation of the SMOSFET demand is 20 %. For SM-BJT, we had an expected demand of 200 wafers per week and a relative standard deviation of 58 %. To make this information compliant with the uniform distribution, we calculated the demand deviation of $D_{\text{inf}} = 346$ and $D_{\text{sup}} = 200$ using of the standard deviation formula of the uniform distribution ($\sigma = \sqrt{\frac{b-a}{2\sqrt{3}}}$) (Lee et al. 2000). Finally, we extracted the weighted average cost of capital (WACC) from the case company's annual report. Since demand and capacity information is on a weekly basis, the WACC had to be converted from a yearly to a weekly basis as well, which results in an interest rate of$i = 0.0018$. The weekly basis makes it even more reasonable to use the perpetuity for discounting.

To calculate the cash outflows, we had to determine the process factor. In our case, we were given the information that the investment in the new machine enables the providing process to reallocate the capacity of 300 SMOSFET wafers per week to produce 200 SM-BJT wafers per week, which leads to a flexibility level of $F = 30$ %. This level of flexibility was chosen to satisfy the expected demand for SM-BJT. To establish this level of flexibility, the company had to invest 3 million EUR in the new machine. The combination of these facts allowed us to determine the value of the term $G \cdot r$. If we insert the level of process flexibility and the investment in the cash outflow function, it results in a combined process and scaling factor of $G \cdot r = 33{,}333$ EUR.

Having collected all necessary data, we can now calculate the cash inflows and outflows with respect to the chosen level of flexibility. As the cash outflows were given, we first check if this investment in process flexibility of 3 million EUR pays off if we solely consider the cash inflow effects of the generated flexibility. Based on the data, we get additional weekly cash inflows of about 29,224 EUR. Using the perpetuity, the risk-adjusted expected present value amounts to 16,235,632 EUR, which exceeds the investment outflows by far. The second question we answer is whether the investment in the new machine is also optimal. To calculate the optimal level of process flexibility for this case, we used an adapted optimization formula because of the missing top-most layer of the decision tree from Figure 1. We obtain an optimal level of process flexibility of $F^* = 26.86$ %, which causes cash outflows of 2,404,047 EUR and weekly cash inflows of 28,243 EUR. After applying the perpetuity, the risk-adjusted expected present value of the cash inflows amounts to 15,690,311 EUR. The cash outflows are lower than the investment initially considered by the case company. The cash inflows are also lower than in the initial setting because of the decreased potential to reallocate capacity. If one compares both cases, the optimal level of process flexibility creates additional value of 50,632 EUR.

Henceforth, we discuss the applicability of our model to the given context. Then, we discuss the impact of the optimization model from the company's perspective as well as the learnings from our own perspective.

In order to make the model applicable to the case at hand, some simplifications had to be made. The first simplification is the assumption that the wafer production process solely consists of two or three process steps, respectively. If we included the entire process, the scaling factor and the costs of process flexibility would increase. Second, the cash outflows could not be determined exactly in advance because they are subject to uncertainty, too. Moreover, in a real-world case the investment decision may not be continuous and therefore one cannot chose a flexibility project that exactly generates the level of process flexibility the optimization model determined as optimal. In the case at hand, the process factor did not have to be calculated separately as, unlike in other cases, it could be determined based on an existing investment. The third point to consider is that the examined production processes are rather special. That is, a semi-conductor factory is very flexible per se and can create more than 1,000 process outputs. As a result, if we compare the investment of about 2.4 million EUR necessary for 27 % of flexibility with the additional cash inflows of 29,224 EUR per week, it becomes evident that process flexibility is very cheap in this case.

Overall, the company benefited from the application of our optimization model, as it helped the company to critically challenge its investment in the new machine by evaluating the investment from an economic perspective. The results indicate that the investment was justified, but that there also was a better solution. Further, it is not optimal to strive for the level of process flexibility that is necessary to cover the expected demand for SM-BJT. This is because, in contrast to the valuation calculus used by the case company, the optimization model considers the demand deviation. The optimization also underlined that striving for the highest level of process flexibility would not have been reasonable although process flexibility turned out to be quite cheap in the case at hand. To measure the impact of the optimal investment decision, some additional performance measures are imaginable. For example, the throughput time, length of the waiting queue, or workload seem to be appropriate. However, the given data was not sufficient to calculate these measures. The only thing we can do is reasoning about how such measures might be affected. For example, the workload of the providing process, i.e., the SMOSFET production process, is likely to decrease and the waiting queue of the superior product, i.e., SM-BJT, should increase if we decrease process flexibility – and vice versa.

From our own perspective, we were able to gain valuable insights by applying the optimization model. We learned that gathering the necessary data turned out to be easier than we expected, since a lot of data was already at hand and as the company was familiar with the concept of the exchange rate. Thus, our future research could build on these concepts as well. Moreover, we first did not find a perfectly fitting case in the company. Nevertheless, as already stated, after slightly modifying our model, we were able to apply the optimization model to a setting where only one process already existed. This showed us that the area of application for our model is broader than we thought in the first place. This also was the reason why we included the case in this paper.

Conclusion

In this paper, we presented an optimization model that helps determine the optimal level of process flexibility, which we define as the percentage of the capacity that can be reallocated from one process to another. The model meets the existing challenges related to the economic valuation of process flexibility by paying attention to positive economic effects of process flexibility and considering uncertain demand in a multi-process context. The model is also based on concrete process characteristics such as criticality and similarity. By considering the cash effects of process flexibility, a multi-period planning horizon, and risk in the form of a risk-adjusted interest rate, the optimization model complies with the principles of value-based BPM. Due to its general form, the optimization model can be applied in a straightforward manner to all processes whose output is sold to customers. We demonstrated the applicability of the optimization model by using it in the context of a company from the semi-conductor industry. Nevertheless, the model is beset with the following limitations that should be subject to further research:

1. Just like in each modeling project, we had to make some simplifying assumptions in order to maintain practicability, analytical solvability, and applicability to a large number of different processes. As we already pointed out in the application section, the assumption of a uniformly distributed demand for the process outputs is an example for such a simplification. Further research should explore which of the optimization model's assumptions can be reasonably relaxed.
2. In its current two-process version, the optimization model focuses on making the process flexible that produces the inferior output, i.e., the output with the lower profit. Thereby, we systematically neglect that the process that produces the superior output may benefit from flexibility as well. If one considered that both processes can be made flexible to a different level, more cases that occur in the real world could be covered. One example is when excess demand for the inferior output and demand shortage for the superior output occur at the same time.
3. By paying particular attention to the complex cash inflow effects of process flexibility, we modeled the cash outflow function in a rather coarse-grained manner. Although important factors such as project overhead and process characteristics were incorporated, a more sophisticated treatment of the cash outflows could increase the fit of our optimization model with the real world. For example, other factors influencing the cash outflows could be identified by empirically analyzing flexibility projects from the real world.
4. After a case example from the manufacturing context, we strive to apply the model to cases from other domains, such as the services domain, where information technology is more involved than in the case presented here. In the services domain, call centers may offer some suitable cases. Consider, for instance, two divisions of a company, one for outbound calls (e.g., life insurance advertisement) and another for inbound calls (e.g., servicing credit card customers). Our optimization model could be employed to determine the optimal investment in cross training and software support, e.g., the shared usage of Web services, for both processes to establish a distinct level of process flexibility.

As already stated in the application section, process design decisions depend on numerous facets in the real world, whereof process flexibility is only one. Examples for such facets are sourcing, automation, or standardization. Further research should therefore conceive a unified framework that integrates decisions on the optimal level of process flexibility with other relevant facets of process design. However, for each extension the advantages and drawbacks have to be weighted carefully. One has to keep in mind that the optimization model intends to purposefully abstract from the real world and not to capture all of its complexity. Thus, it is imperative to deliberate whether a potential increase in closeness to reality out-values the increase complexity and the additional effort of eliciting values for the input parameters.

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