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Interchangeable Product Designs for the Increase of Capacity Flexibility in Production Systems

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Abstract

In the current competitive market, production companies are driven by significant price pressure, as well as high fluctuation in demand. They are faced with the challenge of producing products cost-effectively. Serial and variant manufacturers especially strive for high capacity utilization to prevent overcapacity and to reduce fixed costs in production. Applying current approaches, companies are able to react on market turbulences by adapting the production system within the limits of a defined flexibility corridor. However, these approaches do not eliminate the existence of overcapacity or bottlenecks. An alternative approach for short and medium term adjustments in the given production system has to be developed. In this article, an approach to increase the capacity flexibility in production systems based on the idea of interchangeable product designs is described. The objective is the economical use of overcapacity and efficient reaction to bottlenecks. Based on extensive scientific studies, the influence on the capacity flexibility of production systems by variation of product designs with the same product function, but different manufacturing process times and variable costs, is presented.

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Keywords: Product Function; Product Design; Capacity Flexibility; Production System; Cost Reduction

1. Introduction

Nowadays, many manufacturing companies are constantly confronted with high turbulences in the market. In particular, turbulences are caused by the current economic development, such as globalization, regionalization, individualization and urbanization, which lead to high end-user requirements. New products with short delivery times, high variety and perfect quality at reasonable prices have to be offered [1].

The challenge of manufacturing companies is to produce economically and to be robust against turbulences, in spite of an increasing uncertainty in the dynamic and competitive market. Success and a sustainable future in turbulent markets require high flexibility and fast responsiveness [2].

One success factor of manufacturing companies is having capacity flexibility in response to turbulences, especially to high fluctuation in demand. Today, there are many well-used and practice-oriented approaches to increase the capacity flexibility, such as using flexible machines [3], storages for decoupling [4,5], insourcing and outsourcing [6,7], as well as flexible working time models [8]. The current approaches allow production companies fast adaptions of the production system to changing market conditions, within the limits of an installed flexibility corridor [9].

However, due to the limited flexibility corridor, the optimal capacity utilization cannot be achieved with the current approaches [10]. On the one hand, unused available capacity causes overcapacity and is waste of production resources. Due to high fixed costs, the unused production resources generate costs and thus, a reduction of profits. On the other hand, bottlenecks create immense problems in handling the demand and additionally, imply a loss of profit. The result is a high economic risk and loss of competitiveness that can lead to a threat of corporate existence [11]. Consequently, a new approach has to be developed to extend the corridor and to ensure the optimal capacity utilization.

Therefore, suitable and practice-oriented methods for controlling and reducing the fluctuations in demand have to be provided to manufacturing companies, in order to react purposefully in case of changing market conditions [12,13].

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2. State of the art

The main focus of the following sections is on the capacity flexibility in production systems. For this purpose, the design of a production system and approaches for system modeling are described. Furthermore, the term and characteristics of capacity flexibility are defined and models for the assessment of capacity flexibility are presented. Regarding the presented implementation scenario, the simulation-based optimization method for profit maximization is described.

2.1. Design of a production system

A *production system* can be defined as an organizational, technical and cost-independent allocation of potential factors for production [14]. In terms of the system theory, the levels of a production system can be divided into factory, segment, line and work station [15]. The *factory level* includes the land, buildings and environment, as well as indirect processes (e.g. construction). On *segment level*, the indirect functions (e.g. maintenance, production planning), the production type for each segment (e.g. variant or mass production) and the layouts are defined [16]. On *line level*, production principles (e.g. group or flow production) and the necessary logistic concepts have to be determined [17]. On lowest level, the production resources for each *work station* are planned, based on manufacturing concepts and technologies [18].

According to GUTENBERG, a production system contains the *production resources*, such as manufacturing, material and human resources [19,20,21]. The objective, combining the production resources, is the optimal resource composition for an efficient and flexible production [22]. *Manufacturing resources* can be described as the totality of the equipment and facilities that are used for the operational transformation process [23,24]. The *material resources* are used for the production of products and can be considered as parts of the products or as additives [25]. *Human resources* are employees, performing in an institutional organization for remuneration. Every employee of the organization is defined by a given function (e.g. machine operator) and the associated tasks (e.g. manufacturing) [26,27].

Based on structured, consistent and standard elements, the *system modeling* is used to *design an abstract model* of a production system. Based on the model complex correlations, conditions, processes and effects of a production system can be explained. An abstract model of a production system consists of a set of elements that are related to each other by their characteristics and abilities. The elements can be assigned to subsystems that are characterized by their hierarchical, structural or functional classification in the overall system [28-30].

2.2. Capacity flexibility

Capacity flexibility is defined as the ability to ensure reversible, economic capacity adjustments in a manufacturing system, by using a defined bundle of measures. The bundle of measures focuses on the optimal capacity utilization of manufacturing, human and material resources [31-33].

The request for highly integrated capacity flexibility in production systems is caused by turbulences in the company's environment [34]. The most observed turbulence is caused by the market. Precisely, the *fluctuation in demand* has a strong impact on the capacity utilization and consequently, on the production costs [35]. For identification of fluctuation, scenario-based forecasting methods or time series analyzes are used to predict changes in the market and to determine volumes and capacity requirements in advance [36,37].

2.3. Capacity flexibility corridor

The capacity flexibility is defined by the dimensions *time*, *scope* and *costs* [22]. The first dimension describes the *time for changes*, the second dimension is defined as an established *scope of action* with flexibility potentials and the third dimension illustrates the *costs for system adaptions* and *implementation* of flexibility measures. The highest impact on the capacity flexibility is given by the scope of action that defines the size of the so-called *capacity flexibility corridor*.

The flexibility corridor can be described as a technical and organizational performance bundle of production resources, which can be larger or smaller, depending on the adaptability of each individual resource. According to KALUZA, the size of the performance bundle is given by the combination of the manufacturing, material and human resources, as well as their associated characteristics [38].

The *characteristics of manufacturing resources* with high impact on the manufacturing design and thus, on the capacity flexibility, are determined as: *efficiency and versatility*. The efficiency of manufacturing resources is defined by the available capacity, production volume, technical availability and process time [39-41]. The versatility of manufacturing resources can be measured by the functional performance level and the ability of manufacturing products without any set-ups, despite different product designs [42].

Regarding the *characteristics of material resources*, the following factors have an influence on the product design and thus, on the capacity flexibility: *general parameters, product architecture, product function and material availability*. The general parameters can be summarized as geometric, technical and physical characteristics of material resources [43,44]. The *product architecture* is determined by the characteristics such as complexity, variety, modularity and standardization [45]. A *product function* is defined by the task that has to be accomplished by the design of products, components or parts [46,47]. The *material availability* is mainly determined by the company's suppliers and intra-logistics of the production [48].

The *characteristics of human resources*, with impact on the capacity flexibility, are as follows: *worker qualification and availability*. The *qualification* includes all factors, such as knowledge, skills and attitudes of an employee [49,50]. The *availability* of the human resources is determined by the given working times and the available workers on the market [51].

2.4. Assessment of capacity flexibility

The assessment of the capacity flexibility in production systems is based on historical and future parameters [52], as well as feature-oriented and economic indicators [53]. The particularity of the approaches by ROGALSKI and MÜLLER, is the modeling of the entire production system, including all system levels and characteristics. According to the authors, the assessment of the capacity flexibility is carried out by determining the flexibility corridor, taking into account the variable and fixed costs for the calculation of the total profit. The flexibility corridor is limited by the minimum required capacity and the maximum available capacity. The minimum capacity is given by the economic limit (profit equals zero) and the maximum capacity by the measures for increasing the capacity flexibility, installed in the production system [22,54].

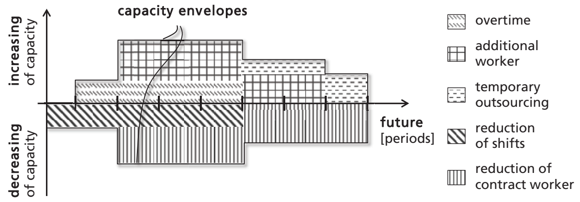

Fig. 1. Profile of capacity envelopes [55].

GOTTSCHALK enhanced these approaches by developing a model, using so-called *capacity envelopes*. In addition to the minimum and maximum capacity, the model considers the adjustment times for the implementation of measures to adapt the available capacity (see Fig. 1). Depending on the measures, the curve for the available capacity can have a positive or negative trend with discrete capacity jumps [55].

2.5. Simulation-based optimization method

Regarding the implementation scenario, a *simulation-based optimization method* can be applied. The method allows to improve production processes, to identify problems at early stages, and to make safe decisions to system adaptions.

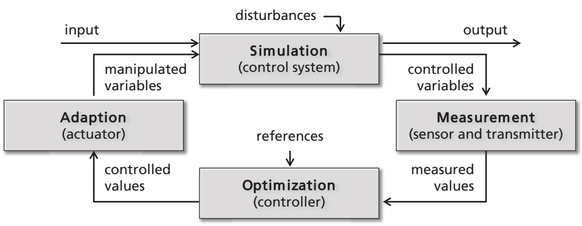

Fig. 2. Control loop of the simulation-based optimization method [56].

The procedure of a simulation-based optimization method can be illustrated as a control loop, as shown in Fig. 2. For the development of a simulation model (control system), the *dynamic event-driven process simulation* is generally used. Here, the simulation model is based on an abstract model of the production system [57]. For the implementation of the optimization model (controller), single- and multi-objective methods can be used. However, to maximize the profit, a single-objective method for the exact or heuristic calculation of the local or global optimum is required [58]. The most commonly used algorithm for solving such linear optimization problems is the *simplex algorithm* [59].

3. Approach

The objective of the approach, so-called *interchangeable product designs,* is that over capacity can be economically used to reduce variable costs and to respond optimally to bottlenecks.

3.1. Interchangeable product designs

The presented approach is, manufacturing two different product components with the same function and customer requirements but two component designs simultaneously. One of the component designs needs a high process time with low variable costs, the other one a low process time with high variable costs. Thus, two component variants with different designs and variable costs allow the use of the manufacturing process time as an additional control variable.

The following example illustrates the difference between two component designs (see Fig. 3). It is required that both component designs perform the same product function and are interchangeable. Here, the technology is injection molding as an integrated manufacturing process in a production system. The component design 1 consists of the molded body with integrated thread which can be made by a single injection molding shot. In contrast, the component design 2 is identical in function but consists of two parts. The injection molded body is an internally produced part, while the thread is realized by a purchased inexpensive metal sleeve.

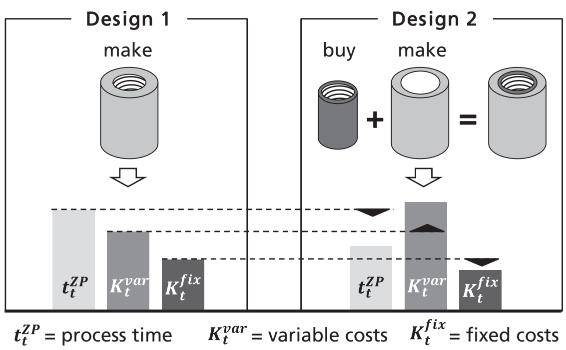

Fig. 3. Characteristics of interchangeable product designs.

The main difference is the process time and the variable costs. Whereas the process time for the injection molding process is higher with design 1 than design 2, the variable costs are lower for design 1. A slight increase in fixed costs for design 1 is recorded for a tool with integrated thread.

3.2. Benefit of the approach

Interchangeable product designs allow an optimal capacity allocation of product components on existing manufacturing resources. In the case of an *over capacity*, the potential cost reduction is shown exemplary in Fig. 4.

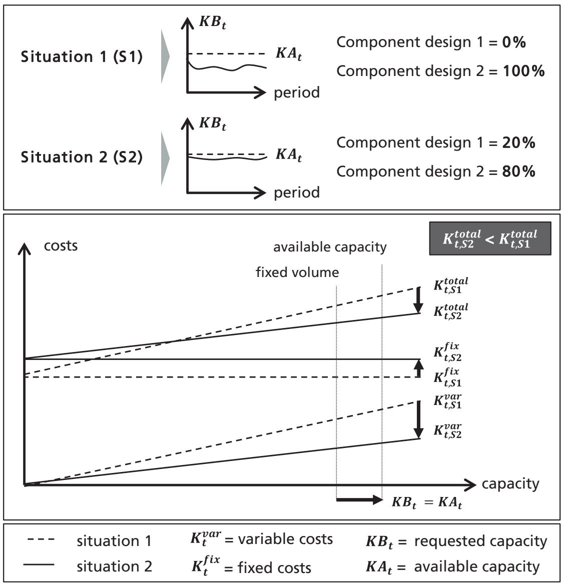

Fig. 4. Optimal capacity allocation for cost reduction.

In situation 1 the requested components are made with component design 2 (short process time, high variable costs). However, since the requested capacity is less than the available capacity, a capacity allocation for components with interchangeable product designs can be executed. The objective is "requested equal available capacity" (see situation 2 in Fig. 4). The result of the capacity allocation is that 20% of the components can be produced with design 1, 80% with design 2. As impact, the variable costs per unit drop and in return, the fixed costs can slightly be raised due to additional investments in tools. Consequently a significant reduction in the total cost is noted (see lower part of Fig. 4).

In the case of a *capacitive bottleneck* in situation 2 an additional capacity allocation can be executed. Instead of an investment in additional equipment, more components with design 2 can be produced. Indeed the variable costs would increase, but a manufacturing company can meet the demand, decrease the opportunity costs, increase revenue and profit with higher production volume, keep fixed costs constant and mainly satisfy the customer by a high responsiveness.

4. Model

In the following, three core modules of a holistic model based on the approach are presented. The modules are divided into *system modeling*, *simulation* and *optimization* (further information about the holistic model see [60]).

For *modeling of the production system*, different variables and characters are used, which allow an abstract, simplified and standardized description of the system elements. In Fig. 5, the objects of a production system and their interdependencies are shown. With regard to the levels of a production system, the production lines and work stations are depicted with a higher level of detail. The figure illustrates that in addition to the production resources, further elements (e.g. flow control) for modeling a production system are required.

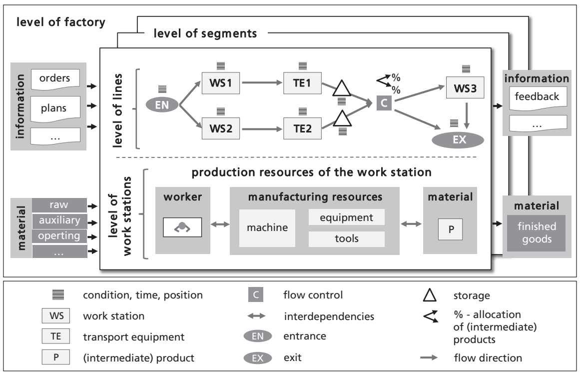

Fig. 5. Modeling of the production system.

Using the *dynamic event-driven process simulation*, the required and available capacity can be calculated. In contrast to static simulation methods, the dynamic simulation method ensures results close to reality. Both the entire material flow control and certain functions for random disturbances can be implemented. The simulation procedure is divided into three phases: preparation, execution and evaluation of the results. During the *preparation phase*, the model of the production system has to be transferred into a simulation model. In the *execution phase*, several experimentation runs are executed for a defined planning period, to calculate the required and available capacity of all implemented production resources. The results are summarized in the *evaluation phase*, in the form of data lists for each production level (factory, line, segment, work station). Subsequently, these data lists are provided for the following profit optimization.

The optimization problem for maximizing the company's profit on work station level can be formulated as follows:

$$\max \; G_t = \sum_{j=1}^{n'} p_{j,t} x_{j,t} - K_t^{var}(y_{j,t}) - K_t^{fix} \tag{1}$$

Constraints:

$$KB_t(y_j) = \sum_{i=1}^{m} t_{i,t}^{ZP}\,(y_{j,t}) \leq KA_t \tag{2}$$

$$KA_t \geq 0 \tag{3}$$

$$\sum_{j=1}^{n'} y_{j,t} = n \quad \wedge \quad y_{j,t} = [0,1] \tag{4}$$

n volume without interchangeable product designs of t
n' volume including interchangeable product designs of t
G_t profit for all products n' of t
$p_{j,t}$ price of product j of t
$x_{j,t}$ production volume of product j of t
$y_{j,t}$ capacity allocation of product j of t
$K_t^{var}(y_j)$ variable costs depending on y_j of t
K_t^{fix} (total) fixed costs of t
$t_{i,t}^{ZP}\,(y_j)$ process time of work station i depending on y_j of t
$KB_t(y_j)$ requested capacity depending on y_j of t
KA_t available capacity of t

According to the presented approach, it is determined: if $t_{i,t}^{ZP,Design\,1} < t_{i,t}^{ZP,Design\,2}$, then $K_t^{var,Design\,1} > K_t^{var,Design\,2}$, Conversely: if $t_{i,t}^{ZP,Design\,1} > t_{i,t}^{ZP,Design\,2}$, then $K_t^{var,Design\,1} < K_t^{var,Design\,2}$. The inequations show a direct interdependency between the process time $t_{i,t}^{ZP}$ and the variable costs K_t^{var}. The two variables are significantly influenced by the capacity allocation $y_{j,t}$. In current approaches, all products are produced with a unique and standard product design, which means $\forall\, y_{j,t} = 1$. However, the presented approach allows values between 1 and 0, because of producing products with different product designs, process times and variable costs, but with the same product function. Thereby, the required capacity can be flexibly adapted, depending on the current fluctuation in demand. The entire mathematical model of the optimization problem is described in [61].

For instance, it is assumed that a certain overcapacity of defined resources in a production system for $t = 3$ is given $(KB_3(y_{j,3}) < KA_3)$. Using the simplex algorithm, the aim of the optimization problem is to calculate the optimal capacity allocation by varying $y_{j,3}$. Regarding the existing overcapacity in the presented example, more products with the product design 2 have to be produced $(t_{i,3}^{ZP,Design\,1} < t_{i,3}^{ZP,Design\,2})$, in order to harmonize the capacity utilization of the production system $(KB_3(y_{j,3}) = KA_3)$. The potential of producing more products with product design 2, is to decrease the overall costs by reducing the variable costs $K_3^{var}(y_{j,3})$ with $K_3^{var,Design\,1} > K_3^{var,Design\,2}$, and finally, to maximize the profit G_3. The main result will be a cost-optimized and highly utilized production system. The Fig. 6 shows the optimal capacity allocation $y_{j,3}$, by having *interchangeable product designs*. Additionally, the flexibility corridor with the minimum required capacity and maximum available capacity is illustrated.

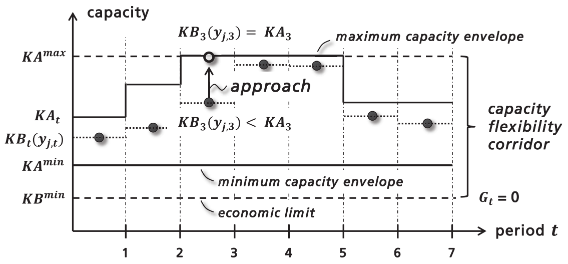

Fig. 6. Optimal capacity allocation by interchangeable product designs.

In comparison to current approaches for the increase of the capacity flexibility, not only the available capacity KA_t, but also the requested capacity $KB_t(y_{j,t})$, can be adapted in order to reduce the costs and to maximize the profit.

5. Implementation scenario

The approach is illustrated, based on a self-implemented simulation model for the production of refrigerators. Volume of the production is about 2 million per year. The simulation model can be created with a software solution of Siemens (*Plant Simulation*) and the optimization problem with *c-plex optimization studio* of IBM.

The main turbulence on the production system is seasonal fluctuations in demand up to 150%. The company produces a product range of more than 40 variants. Based on system modeling, the production system was analyzed, optimized, then abstracted and modeled. Subsequently, the developed production system model was implemented in the form of a simulation model (see Fig. 7). The entire production was roughly reproduced according to the top-down approach, however, the manufacturing cell for the considered foaming process in detail, using a bottom-up approach.

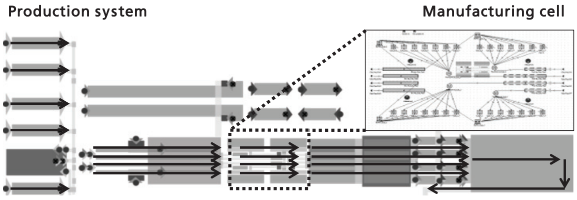

Fig. 7. Modeled production system and manufacturing cell.

The interchangeable product designs are *foam for design 1* and *foam plus vacuum panel for design 2* (see Fig. 8). The function of both component designs is 'insulation'. In the manufacturing cell, the refrigerator is foamed and insulated between inner and outer body. In design 1 more foam is used than in design 2. However, in design 2 an additional vacuum panel is installed in the assembly to get the same insulation values between design 1 and 2.

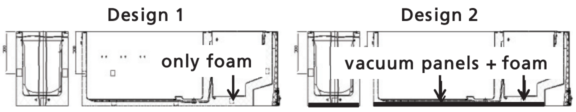

Fig. 8. Functionally identical component designs.

For using the approach the associated functional costs were calculated. Components with design 1 (just with foam) have to be manufactured 20% slower, but can be produced 80% cheaper than components made with design 2 (with foam and vacuum panels). Besides the costs for material, even the labor costs, costs for installing the vacuum panels in the assembly lines as well as fixed costs for adaptation of manufacturing equipment were taken into account.

Recent calculations show the quantitative results that *over capacity* in the manufacturing cell (approx. 4 - 6%) can be used by applying the approach (producing more components with design 1 than components with design 2) to reduce the total costs by > 3% per unit. Additional positive effects are recorded in the case of *bottlenecks*. By producing more components with design 2, the requested capacity has been decreased and the market demand satisfied.

6. Conclusion and outlook

Current approaches concentrate on flexible adjustments of the available capacity to increase the capacity flexibility. However, the presented approach focuses on the adaption of the requested capacity, by using the process time of the manufacturing processes as an additional control variable.

This can be reached by interchangeable product designs with the same product function, but negative correlating process times and variable costs. Depending on the fluctuation in demand, the approach allows the adaption of the requested capacity, the optimization of the capacity utilization and, consequently, the maximization of the company's profit.

After completing the entire model and analyzing the impact of design changes on the potential of the presented approach, a detailed examination of different product and manufacturing designs is necessary. Therefore, design-specific criteria can be defined to identify the potential of products and manufacturing technologies and to create interchangeable product designs.

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