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Increase of Capacity Flexibility in Manufacturing Systems by Substitution of Product Functions

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Abstract

In the current competitive market manufacturing 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. Especially, serial and variant manufacturers strive for high capacity utilization to prevent overcapacity and to reduce their fixed costs in production. By applying current approaches companies are able to react on market turbulences by adapting the manufacturing system in the limits of a defined flexibility corridor. However, with these the existence of overcapacity is not eliminated. In particular, an alternative approach for short and medium term adjustments in the existing manufacturing system has to be given. Consequently, the objective is the efficient use of overcapacity. For this purpose, in this article a new approach to increase the capacity flexibility in manufacturing systems is described. The core approach "Substitution of Product Functions" focuses on manufacturing two different variants of product components with the same product function simultaneously but two different product designs. 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 product designs with differentiation in variable costs allow the use of the factor "manufacturing process time" as an additional control variable for increasing the capacity flexibility. The main result will be a cost-optimized and highly utilized manufacturing process. Based on previous scientific studies in this article the results of the influence on costs and capacity flexibility by variation of the product design and design of manufacturing system are presented.

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Keywords: Product Function; Flexibility; Capacity Utilisation; Manufacturing System; Cost Reduction

1. Introduction

While the world's population in 1950 only amounted to about 2.5 billion people, it has now grown to more than seven billion. McKinsey's extrapolations show that a world population of almost eight billion in 2025 is to be expected. In 1990 there were 1.2 billion people who had more than ten dollars for consumption and by 2025, every second person will be able to contribute to this consumption [1]. The strong world population growth and positive development in consumption will lead to an enormous increase in demand. Because of today's globalization, companies will also be affected by an immense boom in sales [2]. However, the opening and expansion of markets will cause an additional increase in market competitors and have a negative impact on the competitiveness of manufacturing companies [3,4].

Customers will get the opportunity to compare and to choose different offers based on their preferences. This will cause high fluctuations in demand and uncertainty in the capacity planning of manufacturing companies [2]. In Fig. 1, the fluctuation in demand is shown for the manufacturing sector. An enormous drop in incoming orders between 2007 and 2009 can be noted, which caused turbulences and economic crises such as corporate bankruptcies.

Based on this background, the decrease of predictability of markets as well as strongly fluctuating incoming orders can be regarded as the essential factors that are responsible for the occurrence of strong turbulences in the manufacturing sector. Therefore, the challenge for manufacturing companies is to find approaches to increase the capacity flexibility in their manufacturing systems, as well as to survive the dynamic and competitive market [5].

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Fig. 1. Fluctuations in demand of the manufacturing industry [6].

2. State of the art

Focus of the following sections is on the *capacity flexibility* in manufacturing systems. For this purpose, the term capacity flexibility will be defined and the benefits of capacity flexibility described. Afterwards, an explanation of the dimensions of the capacity flexibility follows. Furthermore, the procedures for determining the requested and available capacity as well as current approaches for increasing the capacity flexibility are presented.

2.1. Capacity flexibility

The term capacity flexibility is often synonymously used with *volume or quantity flexibility* [7]. Capacity flexibility is defined by SETHI & SETHI, as the ability to operate economically in a manufacturing system, at different levels of utilization [8]. TEMPELMEIER uses a similar definition and describes the capacity flexibility as the ability to operate economically, despite frequent changes in throughput [9]. In addition to the analysis of ability, SCHELLMANN observed different measures for the implementation of capacity flexibility. According to the author, capacity flexibility is the total of available measures, which allow reversible adaptions of the capacity in work stations and production systems. These measures include adaptions of the capacity of production resources, such as machines and equipment, as well as human resources [10].

Derived from the given definitions, a universal definition for the presented article can be made. Therefore, *capacity flexibility* is 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.

2.2. Benefits of capacity flexibility

To represent the benefits of using approaches to increase the capacity flexibility a general definition of the benefits of flexibility will be generated. According to KALUZA, the benefit of flexibility is defined as enhanced achievement of objectives, by having the possibility to make quick adaptions in case of disturbances or market changes [11,12]. The implied benefit refers to situations of future uncertainties. Therefore, the benefit of implementing measures for capacity flexibility can only be identified right after the occurrence of a change in the manufacturing system. In general, the implementation of any flexibility measures can be compared to an investment problem with risks. Flexibility measures initially incur costs and future cash flows are uncertain [11].

The benefit of capacity flexibility is particularly evident in the increase in competitiveness. On the one hand, the advantages are in the possible manufacturing of customer demand, but on the other hand, they are evident in increase in profitability [13,14]. Increase in profitability means to make profit and is the core aim of any company. If a company is not able to make profit even in times of crises, it will not prevail over its competitors and will disappear sooner or later from the market [15].

In particular, high capacity flexibility plays an important role in corporate existence. Capacity flexibility can be the crucial factor for preventing bankruptcies in crises. According to a study of EULER HERMES, most bankruptcies (44%) are in the manufacturing industry. Based on a detailed survey of more than 125 experienced insolvency practitioners, the insufficient transparency (44%), wrong investment (42%) and inefficient production planning (41%) are the most frequent causes of bankruptcies [16].

2.3. Dimensions of capacity flexibility

In general, the dimensions of capacity flexibility are explained in the research work of ROGALSKI. In contrast to the author's breakdown of the dimensions by time, variety and cost, the breakdown by *time*, *scope* and *costs* is preferred [17]. The first dimension describes the *time for changes* in the manufacturing system. The second dimension is defined as an established *scope of action*, with flexibility potentials and the third dimension illustrates the *costs for system adaption* and *implementation* of flexibility measures.

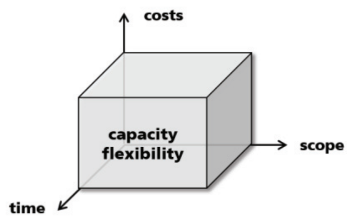

Fig. 2. Dimensions of the capacity flexibility.

In Fig. 2 it is shown that a so-called *tensor of flexibility* is created by the dimensions of flexibility. The highest impact on the capacity flexibility is given by the second dimension of the tensor (scope of action). Depending on the characteristics of one of these three dimensions, the *size of the tensor* and the *degree of capacity flexibility* for an established manufacturing system is determined.

During a change process, a temporal effort (*time*) arises. The effort is created firstly, by identifying a need for action and secondly, by applying flexibility measures in the manufacturing system [18]. The temporal components are divided into reaction time and adaption time. The response time results from the sum of time for the perception, recognition and identification of a problem. During the adaption time the required flexibility demand is determined and solution-oriented adjustments in the manufacturing system are initiated and evaluated [18,19].

Apart from the dimension time, the degree of capacity flexibility is determined by the size of an established scope of action (*scope*), also called flexibility corridor or valid scope. The scope of action can literally be stretched by a technical and organizational given flexible bundle of production resources, which can be sized larger or smaller depending on the adaptability of each individual element. The bundle must be installed in advance by implementing flexibility measures to ensure fast reactions in case of system adaptions [20,21]. According to KALUZA the scope of action is defined as a combination of the elementary production factors, such as manufacturing and human and material resources, as well as their respective characteristics [22].

The objective of increasing the capacity flexibility in manufacturing systems is, to allow the fast and cost-efficient implementation of flexibility measures (*cost*) [23]. The so-called *flexibility costs* highly depend on the equipment, labor and material costs. Therefore, the cost optimum generally has to be calculated based on the given flexibility bundle, including the present production resources [5,24].

2.4. Requested and available capacity flexibility

The capacity flexibility of a company is defined by the level of requested and available flexibility. To determine the minimum and maximum level of the given capacity flexibility in a manufacturing system, various methods can be used.

The *requested capacity flexibility* is decisively influenced by the ordering behavior of customers and the resulting fluctuations in demand. The main task for manufacturing companies is to analyze the past and future sales volumes, in order to identify the required production capacity and to economically plan long-term investments for production resources. To obtain reliable information, scenario-based forecasting methods are mostly used. These are based on a consolidation of market scenarios and sales forecasts [25-27]. Using scenario-based forecasting methods, volumes are anticipated, however the effects of uncertainty and market dynamics are usually neglected. Therefore, companies are focusing on the evaluation of historical order data with a *time series analysis* in order to obtain additional information about the volume and capacity requirements [10]. One of the most commonly used methods for time series analysis is the so-called *Holt-Winters method*, by which a demand forecast can be calculated, using the triple exponential smoothing [28,29].

Other methods are necessary for the comparison of the required capacity flexibility, to the *available capacity flexibility* given by the implemented flexibility measures in an existing manufacturing system. The method according to ROGALSKI pursues the idea of a flexibility corridor which is limited by the minimum requested capacity and maximum available capacity. Within the corridor, a company is enabled to adjust the capacity level using technical or organizational flexibility measures depending on the market situation. The *maximum available capacity* is defined by the sum of the given flexibility measures, whereas the *minimum requested capacity* is determined by those production volumes, where the break-even-point is exceeded. For this, the break-even-point has to be calculated, where the resulting profit is zero. The essential requirement of ROGALSKI'S model is that the product mix remains constant at any time [17,30]. The Fig. 3 exemplary shows the capacity flexibility corridor depending on the minimum and maximum capacity.

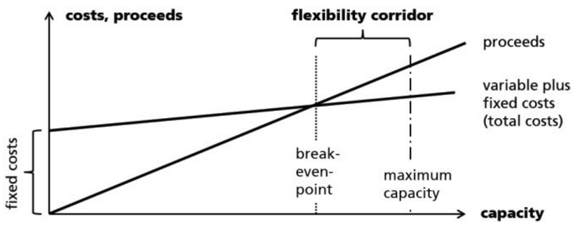

Fig. 3. Definition of the flexibility corridor [17].

MÜLLER adapts the model for discrete jumps of fixed costs caused, by additional required manufacturing resources, to the increase of the available capacity in a manufacturing system. Unlike constant fixed costs, MÜLLER expects investments for flexibility measures in discrete time intervals, depending on changes of the production output. This results in a nonlinear, discontinuous curve for the total costs, which can be shown in a *fixed costs-capacity-diagram*. By adjusting the Fig. 3 at the curve of total costs including discrete jumps, the new curve can be used analogously to determine the minimum and maximum limit of the flexibility corridor [7].

2.5. Current approaches

According to the extensively analyzed literature and work of numerous researchers, there are many useful and practice-oriented approaches to increase the capacity flexibility. These include e.g. flexible machines and equipment [4,31], decoupling by storages [32,33], insourcing and outsourcing [34,35], license models for machinery [36], flexible product design [37,38], flexible working time models and work organization [39], staff recruitment [7] as well as production smoothing [10]. The use of today's approaches allows companies fast adaptions of their manufacturing systems to changing market conditions, within the limits of an installed flexibility corridor [4].

However, due to the limited flexibility corridor, the optimal capacity utilization cannot be achieved with the current approaches [40]. Consequently, a new approach has to be developed to extend the corridor and to ensure the optimal capacity utilization. On the one hand, unused available capacity causes excess capacity and is a waste of production resources. Due to high fixed costs, unused production resources generate costs and thus, a reduction of profits. On the other hand, bottlenecks create problems in the operation of 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 [13].

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 [5,24].

3. Substitution of product functions

In the following sections, the new approach, called *substitution of product functions*, is presented. In addition, a mathematical model is described to explain the correlations and interdependencies of parameters and variables.

3.1. Approach

The approach is based on the idea of the economic use of excess capacity of production resources and the optimal response to capacity bottlenecks. This will be achieved by extending the flexibility corridor to increase the capacity flexibility. The main objective of the approach is to maximize the profits of manufacturing companies.

Essentially, the focus of the presented approach is to manufacture two different variants of product components with the same product function simultaneously, but two different product designs. One of the product designs needs a high process time with low variable costs and the other, a low process time with high variable costs. Interchangeable product designs, with differentiated variable costs, allow the use of *process time* as an additional control variable for increasing the capacity flexibility. The main result will be a cost-optimized and highly utilized manufacturing process.

In [41], further information is given about the general idea of the approach, as well as an application scenario for a detailed explanation of the approach.

3.2. Model

The elements of the approach can be explained using a mathematical model. For the calculation of the limits of the flexibility corridor and maximization of the profit, formulas are required to determine the requested and available capacity, as well as the costs and profits.

In general, the *available capacity* for a defined planning period t can be calculated as follows:

$$KA_t = \sum_{i=1}^{m} t_{i,t}^{AZ} * APV_{i,t} \quad (1)$$

$$APV_{i,t} = \left[t_{i,t}^{AZ} - \left(t_{i,t}^{ZUV} + t_{i,t}^{UGW} + t_{i,t}^{ZR}\right)\right] / \, t_{i,t}^{AZ} \quad (2)$$

$$KA_t, APV_t, t_t^{AZ}, t_t^{ZUV}, t_t^{UGW}, t_t^{ZR} \in \mathbb{R}^m$$

KA_t	Available capacity of all work stations m of period t
$t_{i,t}^{AZ}$	Available working time at work station i of period t
$APV_{i,t}$	Availability of work station i of period t
$t_{i,t}^{ZUV}$	Unplanned preparation time at work station i of period t
$t_{i,t}^{UGW}$	Time for unplanned stops at work station i of period t
$t_{i,t}^{ZR}$	Set up time at work station i of period t

The times for unplanned preparations $t_{i,t}^{ZUV}$ and stops $t_{i,t}^{UGW}$, as well as set ups $t_{i,t}^{ZR}$, are considered in the calculation of the availability of work stations $APV_{i,t}$. The available capacity is determined by multiplying $APV_{i,t}$ with the available working time $t_{i,t}^{AZ}$. The calculation shows that the available capacity can be defined as the real available time for manufacturing.

The *requested capacity* is essentially determined by the process and operating time of manufacturing and human resources. Depending on the type and number of products n (including intermediate and finished products), as well as the work stations m, the requested capacity can be calculated with the following formulas:

$$KB_t = \sum_{i=1}^{m} t_{i,t}^{ZP} \quad (3)$$

$$t_{i,t}^{ZP} = \sum_{j=1}^{n} t_{i,j,t}^{ZB} * x_{j,t} \quad (4)$$

$$KB_t, t_t^{ZP}, t_t^{ZB} \in \mathbb{R}^{m*n};\; x \in \mathbb{R}^n$$

KB_t	Requested capacity for products n at work stations m of t
$t_{i,t}^{ZP}$	Process time for products n at work station i of t
$t_{i,j,t}^{ZB}$	Operating time of product j at work station i of t
$x_{j,t}$	Production volume of product j of t

Based on the approach, the simultaneous production of period t of product components, with interchangeable product designs but the same product function, is required. Therefore, one part of the products n is manufactured with a unique product design of each product component and the other part with interchangeable product designs. The set of all products which is influenced by interchangeable product designs is defined as l. The resulting total set of all products including all versions of product designs as n'. For products with interchangeable product designs, the capacity allocation of product components to manufacturing resources is given by $y_{j,t} \in \mathbb{R}$. The capacity allocation describes how much percent $y_{j,t}$ of the requested volume $x_{j,t}$ of each product j has to be produced at each work station i.

The development of additional versions of product designs can lead to the adaption of the manufacturing design. The manufacturing design determines the operating times $t_{i,t}^{ZB}$ and set up times $t_{i,t}^{ZR}$ of the manufacturing resources. Therefore, the parameters affected by the manufacturing design are marked with FD. Based on these requirements, the formulas for the calculation of the requested and available capacity have to be changed as follows:

$$KA_t = \sum_{i=1}^{m} t_{i,t}^{AZ} * APV_{i,t} \quad (5)$$

$$APV_{i,t} = \left[t_{i,t}^{AZ} - \left(t_{i,t}^{ZUV} + t_{i,t}^{UGW} + t_{i,t}^{ZR(FD)}\right)\right] / \, t_{i,t}^{AZ} \quad (6)$$

$$KB_t = \sum_{i=1}^{m} t_{i,t}^{ZP(FD)} \quad (7)$$

$$t_{i,t}^{ZP(FD)} = \sum_{j=1}^{n'-l} t_{i,j,t}^{ZB} * x_{j,t} + \sum_{j=n'-l+1}^{n'} t_{i,j,t}^{ZB(FD)} * x_{j,t} * y_{j,t} \quad (8)$$

$$\sum_{j=1}^{n'} y_{j,t} = n \quad \wedge \quad y_{j,t} = [0,1] \quad (9)$$

In today's approaches, it is defined that $\forall\, y_{j,t} = 1$, because of manufacturing every product with a unique product design. However, according to the presented approach, it is allowed to accept values for $y_{j,t}$ between 0 and 1 for those product components with the same product function but different product designs. In this case, the important requirement for the capacity allocation is that the operating times for manufacturing of product components with interchangeable product designs are always unequal $\left(t^{ZB(FD1)} \neq t^{ZB(FD2)}\right)$. This creates the possibility to adapt the requested capacity KB_t despite fluctuation in demand of the production volume $x_{j,t}$. Therefore, the optimal capacity allocation is given when $KB_t = KA_t$. An excess capacity is defined by $KB_t < KA_t$ and a bottleneck by $KB_t > KA_t$.

In addition to determining the requested and available capacity, the *cost and profit calculation* has to be defined. Considering the approach and the resulting impact of product and manufacturing design, the following formulas for cost and profit can be derived:

$$K_t^S = K_t^H + (k_t^{EK(PD,FD)} + k_t^{VW} + k_t^{VT}) \tag{10}$$

$$K_t^H = K_t^{var} + K_t^{fix} \tag{11}$$

$$K_t^{var} = \sum_{i=1}^{m}(\sum_{j=1}^{n'-l}\left(k_{i,j,t}^{FM} + k_{i,j,t}^{UMG} + k_{i,j,t}^{FL}\right) * x_{j,t} + \sum_{j=n'-l+1}^{n'}\left(k_{i,j,t}^{FM(PD)} + k_{i,j,t}^{UMG} + k_{i,j,t}^{FL(FD)}\right) * x_{j,t} * y_{j,t}) \tag{12}$$

$$K_t^{fix} = \sum_{i=1}^{m} k_{i,t}^{EMG(PD)} + k_{i,t}^{SEK(FD)} + k_{i,t}^{BMFG(FD)} + k_{i,t}^{PLFG} \tag{13}$$

$k_t^{FM}, k_t^{FM(PD)}, k_t^{UMG}, k_t^{FL}, k_t^{FL(FD)} \in \mathbb{R}^{m*n'}$;
$k_t^{EMG(PD)}, k_t^{SEK(FD)} k_t^{BMFG(FD)}, k_t^{PLFG} \in \mathbb{R}^{m}$

K_t^S	Total costs for products n' at work stations m of t
K_t^H	Manufacturing costs for products n' at work stations m of t
$k_t^{EK(PD,FD)}$	Development and construction costs of t depending on PD/FD
k_t^{VW}, k_t^{VT}	Administration and sales costs of t
K_t^{var}	Variable costs for products n' at work stations m of t
K_t^{fix}	Fixed costs at work stations m of t
$k_{i,j,t}^{FM}$	Manufacturing material costs of product j at work station i of t
$k_{i,j,t}^{FM(PD)}$	Manufacturing material costs of product j at work station i of t depending on PD
$k_{i,j,t}^{UMG}$	Indirect material overhead costs of product j at work station i of t
$k_{i,j,t}^{FL}$	Wages for product j at work station i of t
$k_{i,j,t}^{FL(FD)}$	Wages for product j at work station i of t depending on FD
$k_{i,t}^{EMG(PD)}$	Direct material overhead costs at work station i of t dep. on PD
$k_{i,t}^{SEK(FD)}$	Additional manufacturing costs at work station i of t dep. on FD
$k_{i,t}^{BMFG(FD)}$	Overhead costs for manufacturing resources at workstation i of t depending on FD
$k_{i,t}^{PLFG}$	Overhead costs for human resources at workstation i of t

According to the presented approach in this article it is defined: if $t^{ZB(FD1)} < t^{ZB(FD2)}$, then $k^{FM(PD1)} + k^{FL(FD1)} > k^{FM(PD2)} + k^{FL(FD2)}$. Conversely: if $t^{ZB(FD1)} > t^{ZB(FD2)}$, then $k^{FM(PD1)} + k^{FL(FD1)} < k^{FM(PD2)} + k^{FL(FD2)}$. Therefore, a direct interdependency between the process time $t_{i,t}^{ZP(FD)}$ and the variable costs K_t^{var} exists. The two variables are significantly influenced by the capacity allocation of $y_{j,t}$.

Based on the cost calculation, the following formulas for the calculation of the profit G_t and the associated proceeds e_t are described by:

$$G_t = \sum_{j=1}^{n'} p_{j,t} x_{j,t} - K_t^S \tag{14}$$

$$e_t = \sum_{j=1}^{n'} p_{j,t} x_{j,t} \tag{15}$$

G_t	Profit for products n' of t
$p_{j,t}$	Price of product j of t
e_t	Proceeds for products n' of t

Now, the limits of the flexibility corridor FLK_t can be defined by determining the minimum requested capacity KB_t^{min} (lower limit) and maximum available capacity KA_t^{max} (upper limit). The requested capacity KB_t^{min} depends on the profit G_t and is given for $G_t = 0$, whereas the available capacity KA_t^{max} is defined by the implemented approaches for the increase of the capacity flexibility in an establish manufacturing system.

In Fig. 4, the possible extension of the *flexibility corridor*, by applying the presented approach, is illustrated. The figure shows both the shifting of KA_t^{max} due to additional set up times (6) and the moving of KB_t^{min} due to the minimization of process times by *substitution of product functions* based on interchangeable product designs (8). Furthermore, the jump of fixed costs K_t^{fix} because of necessary adaptions of the product and manufacturing designs is presented (13), as well as the decrease of variable costs K_t^{var}, by minimizing the total costs for manufacturing material and wages (12) is shown.

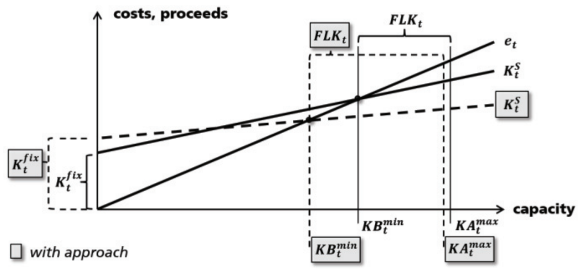

Fig. 4. Increase of capacity flexibility.

Overall, the main objective of the approach is to optimize the profit G_t. Therefore, the focus is on the optimal capacity allocation by variation of $y_{j,t}$. Based on that, the following optimization problem is given:

$$\max \; G_t = \sum_{j=1}^{n'} p_{j,t} x_{j,t} - K_t^S\,(y_{j,t}) \tag{16}$$

Constraints:

$$KB_t^{(FD)}(y_{j,t}) \leq KA_t^{(FD)} \tag{17}$$

$$KA_t^{(FD)} \geq 0 \tag{18}$$

$$\sum_{j=1}^{n'} y_{j,t} = n \quad \wedge \quad y_{j,t} = [0,1] \tag{19}$$

The first constraint is required to optimize the capacity utilization, the second to allow only positive available capacities and the third to ensure the same production volume. Due to the generally described mathematical model, the approach can be used in numerous manufacturing systems.

4. Conclusion and outlook

The presented approach allows the extension of the flexibility corridor, which leads to the increase of capacity flexibility. Current approaches attempt to increase the capacity flexibility by flexible adjustments of the available capacity, whereas the approach of *substitution of product functions* focuses on the possibility to adapt the requested capacity, despite an enormous fluctuation in demand. Based on the optimal capacity allocation of product components with interchangeable product designs, but same product functions, the maximization of the company's profit can be ensured.

In the next step further analysis with regard to modeling a manufacturing system as well as the examination of the adaptability of production resources are necessary. Therefore, the structure of a manufacturing system and the characteristics of production resources have to be considered. In addition to variable and fixed costs, the costs for product functions of individual products will be investigated in order to obtain a better understanding of the correlation between product design and product function. The analysis will help to define a clearly limited field of application of the presented approach. The analysis will be supported by using software solutions to implement various manufacturing system models and the presented mathematical model.

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