Design Principles for an Integrated Product and Process Development Approach for Rotationally Symmetric Products

Guenther Schuh, Till Potente, Christina Thomas, Stephan Schmitz, Jonas Mayer
Machine tool laboratory WZL RWTH Aachen University, Germany

Abstract--**Highly customized products lead to irreproducible complexity in product development and manufacturing. Additionally order processing becomes very complex. Today's product design and IT-tools reduce this complexity insufficiently. Potentials in administration and manufacturing are not fully in line. Most of the relevant approaches for designing products focus on the product without considering interactions with manufacturing. Approaches within concurrent engineering predominantly support optimization of single components rather than modular product platforms. The presented approach develops constituent features by setting product and manufacturing-process standards for modular product platforms. These constituent features describe product characteristics that have a critical impact on product and manufacturing complexity. These features don´t affected customer demands and therefore can be standardized. The key factor to derive constituent features is to quantify the variance-sensitivity of product features . Variance-sensitivity is a measure of the costs required to produce product variance. Hence highly diverse variance-sensitive features lead to additional expenses in manufacturing-processes. The aim of this paper is to develop an approach to statistically quantify the variance-sensitivity in order to set constituent features for rotational symmetric products. Knowledge of the influence between product features and manufacturing-process enables companies to offer customized products with cost-effective manufacturing-processes. This technological and production-related flexibility is essential for the growing needs of global markets.**

I. INTRODUCTION

High product variety, strong fluctuant batch sizes and volatile demands are today's problems of manufacturer of small batch series within the plant and machinery industry [42]. Since rotationally symmetric products have a high significance in today's plant and machinery industry, the paper focusses typical challenges manufacturer of small batch series with job shop production are facing [45]. Within metal-working production systems especially metal-cutting manufacturing has a predominance [48]. Highly varying product features are causing a large number of slightly different products and this leads to crossing material flows, fluctuant capacity utilization and instable manufacturing processes [37, 42]. These facts lead to a decrease in productivity of manufacturer of small batch series. The aim of this approach is to identify critical processes in manufacturing and link it to the corresponding product structure and its product features in order to increase productivity of manufacturer of small batch series despite of high product and process complexity. The approach is integrated in a framework for developing modular product platforms based on product and production standards. [32, 40] These standards are responsible for increasing cost-effectiveness by dealing with the descripted product-production complexity [39]. The prerequisite to derive theses standards, so called constituent features, is to analyze the interdependencies within the product-production-system. Dependent on property and number of product variance the production costs vary in manufacturing due to different technologies, tools and stability of a production process. This cost behavior is described as variance sensitivity. Within this paper the approach to determine the variance sensitivity regarding stability of manufacturing processes is presented. Stable production processes with best quality, lowest production costs and shortest lead times require product variants that are adapted to the production solution space. Knowledge about the variance sensitivity enables an economically matching of product- and production system, but needs an systematic identification of critical manufacturing processes. At last constituent product and process features can be derived to design economical rotationally symmetric products, which is subject of future research work and will be presented in future publications.

II. COMPLEXITY IN PRODUCT DEVELOPMENT AND MANUFACTURING

A. Product complexity of rotationally symmetric products

WZL RWTH Aachen (Werkzeugmaschinenlabor – Laboratory for Machine Tools and Production Engineering at Aachen University) industry cases show that companies often have more than 90.000 components and 35.000 products in portfolios that can contain up to 1000 variants of structural and functional similar components [6]. This high external diversity evolves from norms, guidelines and regulations in international companies and the importance of consideration of specific customer demand for manufacturer of small batch series. In this way they increase the individual customer benefits and differentiate themselves from the competitors by a big quantity of products. Although, there are a lot of parts with structural similar components, synergy effects in the product development process and a cost-effective order processing process cannot be realized [40]. A more cost-effective, production-oriented constructive solution is not systematically selectable by the construction engineer due to a lack of evaluation and the high level of complexity. The external diversity also leads to intern diversity, e.g. if existing solutions get lost and new construction plans have to be created [39]. Effects are additional required tools and operation charts, higher set up costs and more complex product management and control [31]. These additional costs create a competitive disadvantage for the manufacturing company [39].

B. Process complexity of rotationally symmetric products

Production creation has a various number of disposable resources, e.g. mechanical fabrication like turning, milling and drilling [6]. Slightly diverse product variants are produced with varying technologies and different processes, which lead to a high process complexity [21]. Due to highly varying processes work scheduler tend to create new working schedules based on their individual know-how instead of using standardized working schedules for diverse product variants. As a result the creation of working schedules increases. Fig. 1 illustrates this fact by presenting an experiment conducted by Halevi [17].

The experiment demonstrates the process variance for drilling a hole of diameter 30mm. This shows how similar or slightly different products can be produced by highly varying processes. The result is a high variation of possible processing sequences and diverse required manufacturing technologies, which lead to high complexity in the flow of material and value adding processes as well as fluctuating capacity utilization [42]. Fig. 2 shows on the left hand side the commonalities of work stations and on the right hand side an analysis of process variance regarding the processing time.

Low process commonalities in production systems of manufacturer of small batch series lead to unpredictable process sequences. Consequential a high variance in the production processes leads to a highly spreading lead time and an unpredictable capacity load. Additionally work scheduler create new working schedules for new product variants instead of using similar or standardized solutions. A lot of similar products emerge a high amount of partly marginally different operation charts in process planning. This does not result in a systematic flow of production but rather in conversion and variation of processing sequences of similar or equal products in manufacturing. Thereby crossing flow of material, fluctuating capacity utilization and scattering processing time have a bad influence on lead times and though on the delivery dependability, which is a key factor of modern just in time production [11]. To improve the delivery dependability, standardized process sequence is a key requirement. The analysis of the process allows the manufacturing-oriented product design, i.e. a stable manufacturing process and flow as well as standardized product manufacturing. Hence processing time and their scattering do not change. In addition, changes may be caused only by random variation and not due to systematic causes [1, 17].

Operations d = drilling s = spindle r = rubbing				# of experts	processing time [min]
d Ø 30				9	0,13-0,58
d Ø 28	s Ø 30			9	0,22-0,65
d Ø 20	d Ø 30			7	0,49-0,84
d Ø 15	d Ø 30			1	0,81
d Ø 10	d Ø 30			2	0,78
d Ø 5	d Ø 30			1	0,81
d Ø 8	d Ø 28	s Ø 30		1	0,86
d Ø 8	d Ø 18	s Ø 30		1	0,77
d Ø 10	d Ø 20	d Ø 30		2	1,04
d Ø 10	d Ø 28,7	r Ø 30		1	1,07
d Ø 10	d Ø 20	d Ø 28	s Ø 30	2	1,13
d Ø 5	d Ø 13	d Ø 22	d Ø 30	1	1,29

Fig. 1 Comparison of expert opinions in work scheduling (Source:[31])

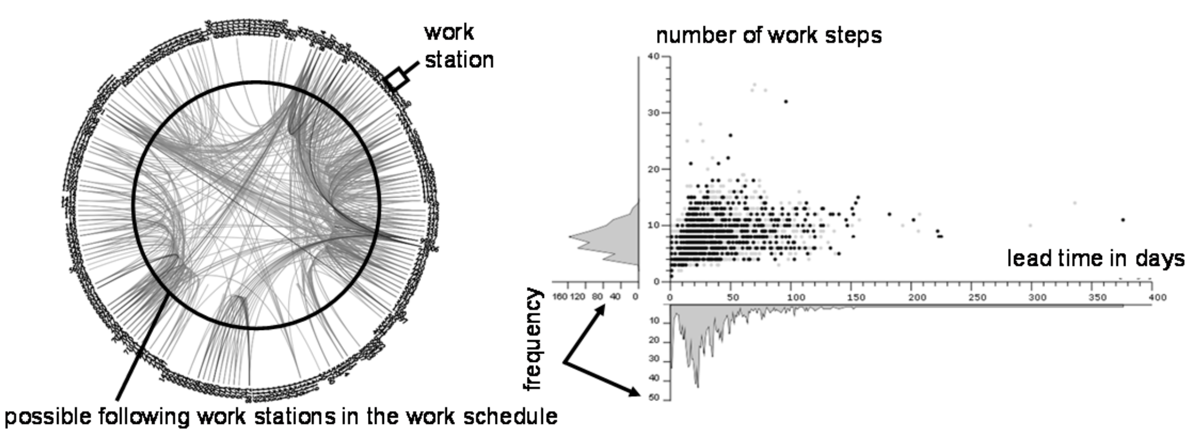


Fig. 2 Process commonalities and spread of lead time of a production system (Source: WZL RWTH industry cases)

C. Challenges and potential in product development and manufacturing

Rationally symmetric products have a high product and process complexity. Fig. 3 shows the area of conflict because of increasing product individuality and its consequences on the value added process described in the introduction.

In summary it can be stated that process complexity leads to the following challenges [3, 4, 5, 14, 20, 29, 46]: Batch sizes decreased by 50%, Profits shrank by 83%, Large changeover times, Higher lead time, High costs, Lower Quality, fluctuant capacity utilization, crossing material flows, unstable manufacture

The consequence is a high amount of planning and coordinating activities within the order fulfillment process. Critical factors for success of that process are standardized product development and economical manufacturing as well as meeting individual customer requirements. A key factor to increase companies efficiency is a production-oriented design, which has a positive effect on through-put time, manufacturing quality, process variation and stability of manufacturing processes [35]. Potential analysis and valuations by the industry elucidate, that a reduction of development time by 11%, planning duration by 30% and cutting of the processing time in mechanical manufacturing by 60%, are possible saving potentials [38]. This optimization potential shows the industrial relevance of the addressed problem.

III. STATE OF THE ART IN PRODUCT DEVELOPMENT AND IT-SUPPORT

A. Deficiencies in product development

Within the past decades, the question of how to fulfill market demands for highly customized products in an efficient and cost-effective way has gained more and more attention. Today it has become a central topic for research in the field of production economics – namely known as the discipline of mass customization. Existing approaches for product design target a solution for the trade-off between economies of scale and individualized, customer-oriented product manufacturing. Fogliatto gives a holistic review of past developments in this field of research [15]. Based thereon, it is suitable to cluster and evaluate the state of the art of product development by using the following simplified model (see Fig. 4).

Any product development approach targets a relevant contribution to the enterprises scope of business, i.e. to draw profit by manufacturing products as desired by the market. One can identify three main categories for product design approaches: the market-pull oriented design, the technology-push oriented design and the production-oriented product development [7, 12, 15, 18, 24, 25, 28, 30, 35, 36, 43, 47, 51, 52]

Deficiencies in market-pull oriented approaches

Methods for product development within this category mainly target the analysis of customer needs and the transfer of the corresponding product functions into an adequate product-architecture. The integration of customers into the product development process experienced significant progress by use of e.g. web-based product configurators [15]. Mittal and Frayman suggest the use of artificial intelligence to analyze the product configurations that are desired by the market [25]. Zha proposes a hybrid system using fuzzy logic to analyze customer preferences which are clustered in a knowledge database [51]. Shao uses data mining techniques to identify correlations between certain customer preferences and try to find customer groups by that [43]. To achieve scale effects in production, several approaches propose methods to set up a product-architecture that either considers the demanded product-key-functions as well as a high commonality within the whole product structure [7, 12, 15, 18, 24, 25, 28, 30, 35, 36, 43, 47, 51, 52]. Main strategies to

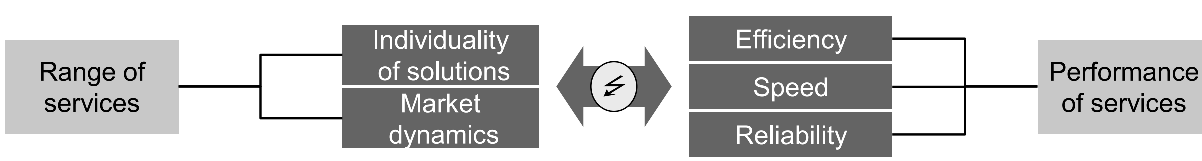


Fig. 3 Area of conflict between range and performance of services (Source: [16)]

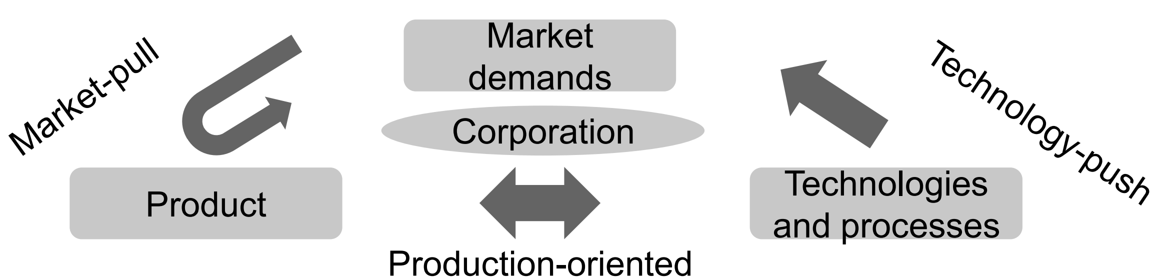


Fig. 4 Approaches within product development (Source: [7])

achieve commonality are product platforms, modularity and building blocks. Erixon, Ericsson, Lindemann and Pimmler propose concepts to identify relations between desired product functions by use of matrix-methods (e.g. the design-structure-matrix) to cluster product functions into modules systematically [12, 30]. These methods focus on the function-structure and do neither consider the constraints of production processes nor give any design guidelines. They stay on a pure functional level of product development. Cai, Nee and Lu suggest the standardization of especially those product features which lead to high variety-costs and therefore introduce indices for the degree of differentiation and commonality of product features [7]. Similar to that, Martin and Kosuke define a "General Variety Index" and a "Coupling Index" to measure the efforts required to change product components as well as the impact of these changes on the design of other components [24]. None of the index-approaches take process-related manufacturing costs and technology-related design-constraints into account concretely. Summing up, market-driven approaches focus on identifying market demands and the translation of customer needs into a well organized function-structure. These methods aim at function modules and platform systems to achieve commonalities and economies of scale. The actual manufacturing costs are not considered. Besides that, these methods do not consider constraints on product design given by used manufacturing technologies. Especially the impact of product features on process features or costs and vice versa are not taken into account for product development.

Deficiencies in technology-push oriented approaches

The technology-push oriented view concentrates on the companies technological competences to derive new product ideas and to found new markets [36]. Herstatt proposes methods to support technology-push product development and the success of these products [16]. Herstatt suggests the anticipation of future market needs and technology potentials e.g. by the use of road mapping techniques. Beyond that, customers shall be confronted with early states of new products e.g. through prototype-testing. This way the development department shall get a customer-feedback for further product design in an early phase of the development process. Schuh and Klappert describe a five-layer model for technology-planning including product- and process technologies, product, customer- and market demands and trends [15]. It is stated that the technology-push oriented view targets the most efficient use of a company's technology-competence for the derivation and development of new products. However, alike other approaches this method stays at a more general level of product development. Concrete suggestions for product design are missing as well as the consideration or quantification of process-product-interferences and -dependencies.

Deficiencies in production-oriented approaches

At current there is a lack of research in the field of product-process-interference and the impact of product features on manufacturing costs [15]. Within a famous and old-established approach Opitz presents a classification system especially for rotationally symmetric products to describe commonalities within product components to standardize working plans [28]. Tu proposes two cost-calculation methods for highly customized product configurations based on cost estimations for the manufacturing and the logistics demand at the level of sub-assemblies, components and component features [15, 47]. Wheelwright and Clark respectively Nevins and Whitney propose the method of concurrent engineering or rather integrated design. This approach enables parallel work of product designers, production planners and manufacturing engineers and supports a connected decision process[27, 49]. Ettlie defines concurrent engineering or rather integrated design as: „Integrated design is the coordinated development effort in timing and substance of the various disciplines and organizational functions that span the life-cycle of new products and services" [13]. Therefore integrated design or rather concurrent engineering focusses on organizational activities within the product development process to optimize single products [27]. However a method to design product-oriented modular product platforms developed by Rudolf concentrates less on organizational activities rather than concrete product- and process design. This methods focusses on selected administrative departments as well as on production and less on complete company [32].

Another approach tries to identify cost drivers of mass customization products by analyzing dependencies between product and process variety [15, 52]. Schuh suggests the analysis of a process' variance sensitivity to identify cost driving product features and the impact of product variety on process costs (see Fig. 5). In this context, variance sensitivity is defined as the dependency between manufacturing costs of a certain process and the variety of product features that are set in this process [35]. The method's first step is the identification of highly variance-sensitive and therefore critical manufacturing processes. Afterwards constituent product features are derived and the gained knowledge about product-process-interdependencies is integrated into the product design process. Constituent features describe standards in product design as well as in production processes. In summary this approach considers the constraints given by production, but a concrete procedure to measure the impact of product and process variety on manufacturing costs quantitatively as well as a practical procedure is still missing. Rudolf uses three steps to derive constituent features for a production-oriented modular platform design (see Fig. 6) [32]. In the first step components with high potentially commonality are identified. Therefore he defines the two indicators "commonality potential variety" and "commonality potential costs", which are charted within a portfolio. In step

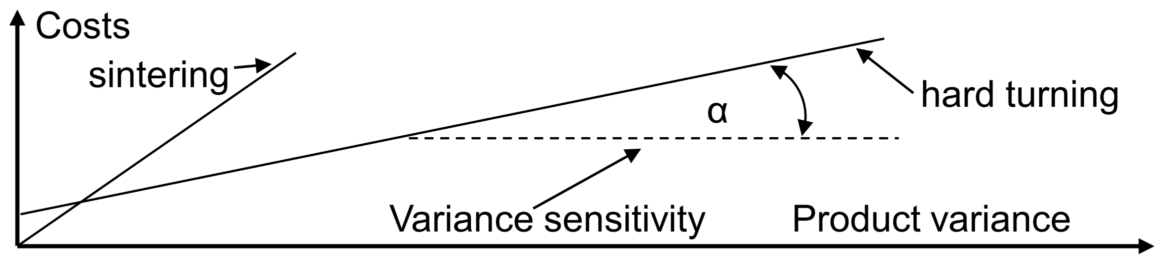


Fig. 5 Variance sensitivity depending on production technology (Source : [35])

two product-process-interactions between those components with high commonality potential are formalized in a variance network based on graph theory. Finally, in the third step, constituent features are derived by using a factor screening and identifying those features, which have the biggest impact in terms of possible savings on the product-production-system.

This approach allows the analytical identification of the variance sensitivity by detecting components with high commonality potential and their qualitative impact on the product-production-system. Nevertheless a quantitative expression based on company data to specify this impact is still missing [32].

B. Deficits of IT-support in product development and manufacturing

Besides the above described product development approaches there are IT-systems to support the product development process as well as manufacturing. Fig. 7 gives an overview of common systems used. The main task of a Manufacturing Execution System (MES) is to collect production referred data in real time so it can be used to control the production processes [50]. A major problem of these manufacturing supporting system is that 60% of the companies only use it as a separate IT-system. The collected manufacturing data is only used for optimizing the manufacturing process without connecting the system with the product development [2]. Besides the data is not referred to the feature but only to the machine or order [33]. A topic paper [38] underlines that there are a lot of IT-Tools, such as ERP-, PDM- and CAx-systems [33, 41, 44] to support the product development process and the order fulfillment process. On the one hand there are PDM and ERP on the product side, on the other hand there is MES with the data from the manufacturing.

The CAx-systems segments between the product and manufacturing side. In summary, although these single IT-solutions work fairly well, today's IT-support with its interface problems amplify isolated applications and a solid structure of company's divisions [42, 43]. Furthermore one can draw the conclusion that important information about product design and its impact on the process chain in manufacturing are not sufficient presented by these tools (see Fig. 8).

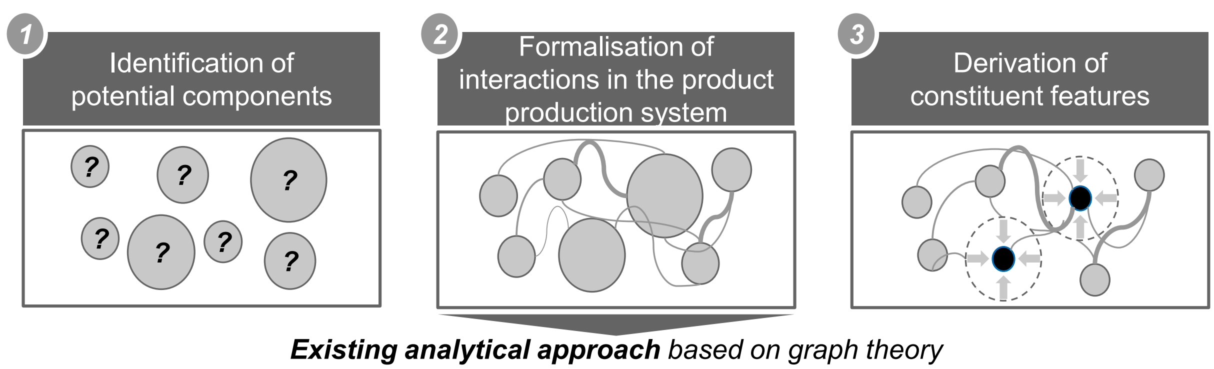


Fig. 6 Three steps of identifying constituent features (Source: [32])

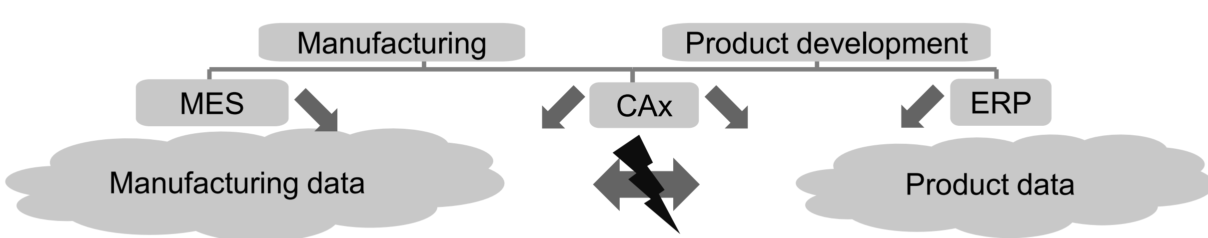


Fig. 7 Deficits of IT-support in product development and manufacturing

Fig. 8 Deficits in using product and manufacturing data in product development

C. Deficiencies in product development and supporting IT-systems

Past research focused on methods to structure product-architectures that maximize the customer value created by product functions. Moreover there exist guidelines of how to develop new products based on the technological potential of a corporation. In both fields, the manufacturing costs of highly customized products have been neglected. The production-oriented approaches try to detect cost drivers throughout the production processes, but still a concrete method to quantify manufacturing costs of a high variety product program and derive a concrete design guideline is missing. Additionally there are IT-systems to support the product development process, but the existing product and manufacturing data are not used sufficiently to detect the cost influence of product variance on manufacturing processes. Therefore a systematic approach to quantitatively identify the variance sensitivity based on company data is missing. In summary this shows the need for a systematic data based approach to quantitatively identify the variance sensitivity for using it in product design to derive constituent features.

IV. STATISTICAL IDENTIFICATION OF VARIANCE SENSITIVITY TO DERIVE CONSTITUENT PRODUCT FEATURES

A. Framework of the approach

As shown in Fig. 6 Rudolf developed an approach to examine the interdependencies between products and their respective manufacturing processes [32]. On the basis of these interdependencies product features with a high cost impact for mounting, indirect and production processes are determined. Product features with a high cost impact represent possible constituent features. The main deficit of the approach is the need for interviews of experts of manufacturing departments as well as a missing quantitative evaluation of variance sensitivity. The present paper focusses on the development of a method which quantifies empirically interdependencies between product features and their respective manufacturing processes in an automated procedure based on company data (see Fig. 9). Apparently, the developed approach aims at eliminating the main deficiency, lacking quantification of product-production interactions in terms of variance sensitivity, of the approach by Rudolf [32]. To describe variance sensitivity it is necessary to determine the main influence factors within a product and production systems.

In this approach we propose number and property of a product feature cause variance sensitivity (see Fig. 10). For a holistic analysis of the variance sensitivity of processes we propose three indicators, namely cost drivers, system boundaries as well as the stability of manufacturing processes (see Fig. 11). Cost drivers influence the main cost of a process in dependency of variable product features such as additional tools. System boundaries describe technical restrictions of manufacturing processes. In the case of a change of product it is possible that system boundaries are exceeded. System boundaries have to be expanded in order to be able to manufacture the product variance. The third variance sensitivity indicator describes the stability of manufacturing processes subject to a changing product variance. Stable processes are characterized by the capability to derive permanent consistent results. In accordance to Hopp and Spearman manufacturing process variability can be categorized in varying process times, low process availableness, machine set ups as well as reworking procedures [19, 44]. Quantitative descriptions of product-process-interdependencies can be systematically described by the variance sensitivity of manufacturing processes.

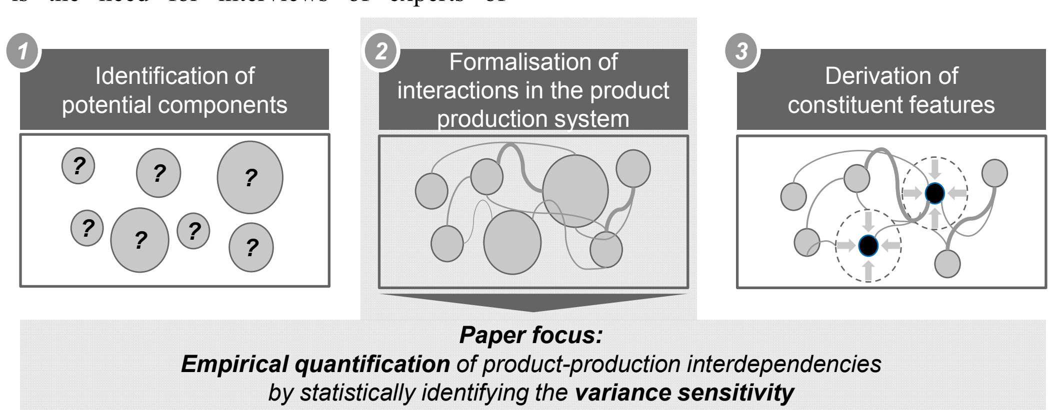


Fig. 9 Framework of the presented approach [3]

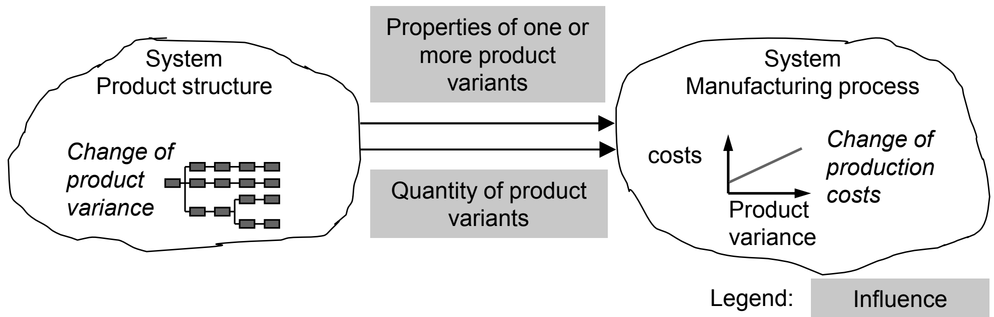


Fig. 10 Influences on variance sensitivity

In this paper we propose a statistical based method for the quantitative identification of the variance sensitivity indicator stability.

The proposed method applies to the command variables process times, setup times, malfunction periods as well as deficient products. Fig. 12 is summing up the focus of the presents approach and provides an overview of the developed variance sensitivity indicators.

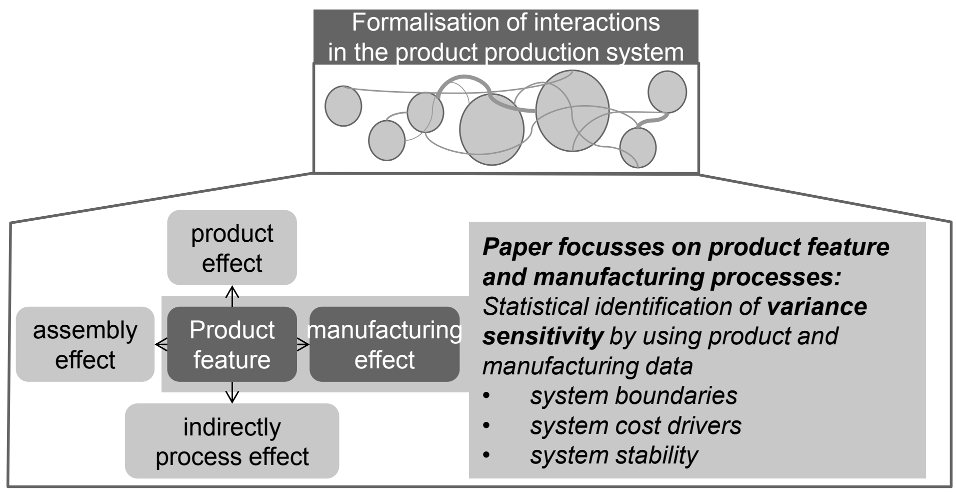


Fig. 11 Focus of the presented approach (Source: [3])

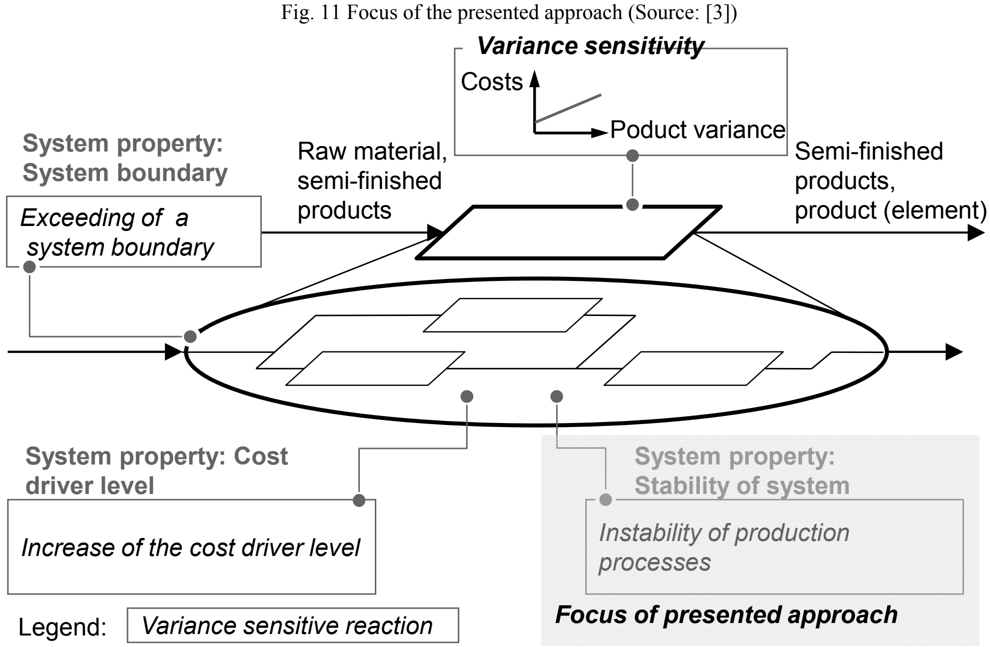


Fig. 12 Statistical identification of the variance sensitivity indicator system stability

B. Approach: Statistical identification of the variance sensitivity indicator stability

Aim of the proposed method is the identification of interdependencies between product features, their characteristics and the production processes out of data provided by MES-systems. The main hypothesis of this paper states that product variance has an impact on the stability of manufacturing processes. Stable manufacturing process will lead to a higher predictability of scheduled delivery date, decrease in throughput times, higher manufacturing quality and lower production costs [23]. In this connection stability states predictability as well as sustainability of equilibrium. An instable manufacturing process is existent, if one of these stability criteria is not achieved. Since MES-systems provide large data quantities a systematic approach is necessary in order to be able to analyze product-process-interdependencies. The knowledge discovery in databases approach provides a framework for the analysis of large data quantities [16]. Data mining techniques as a part of the KDD (Knowledge Discovery in Databases) approach aim at discovering certain patterns in large data quantities.

For these reasons it appears useful to use KDD for data preparation tasks and to apply data mining techniques for discovering not apparent product-process-interdependencies. Therefore, the KDD approach and data mining techniques provide a framework for holistic data analysis of variance sensitivity. In the following chapters the six developed phases for the quantitative identification of variance sensitivity are detailed (see Fig. 13).

Phase 1 - 4: Initial data preparation

Phases 1 to 4 of the method are necessary data preparation steps for the actual data analysis in phase 5. In accordance to the KDD-approach an initial data volume has to be determined in phase 1. As part of the approach of Rudolf an initial set of product variants are identified which are characterized by high levels of complexity costs as well as a high variance [32]. Because of the high levels of these two dimensions, these products have potential for future product standardizations. In the proposed method an additional dimension is added. The focus of the method is the quantification of the variance sensitivity indicator stability in manufacturing environments. As a consequence an initial estimation of the stability has to be derived. This ensures a selection of products which lead to instable processes and have great standardization potential. For this estimation we propose a stability border in the form of a control ellipse (see phase 5 step 3). Product components of one product are compared and instable processes are identified.

In phase 2 data sources which are necessary for the variance sensitivity analysis are identified. Necessary data sources include bill of materials, product specifications, working plans, technology restrictions and production orders. From these data sources information about variance sensitivity with regard to the stability of manufacturing processes are derived.

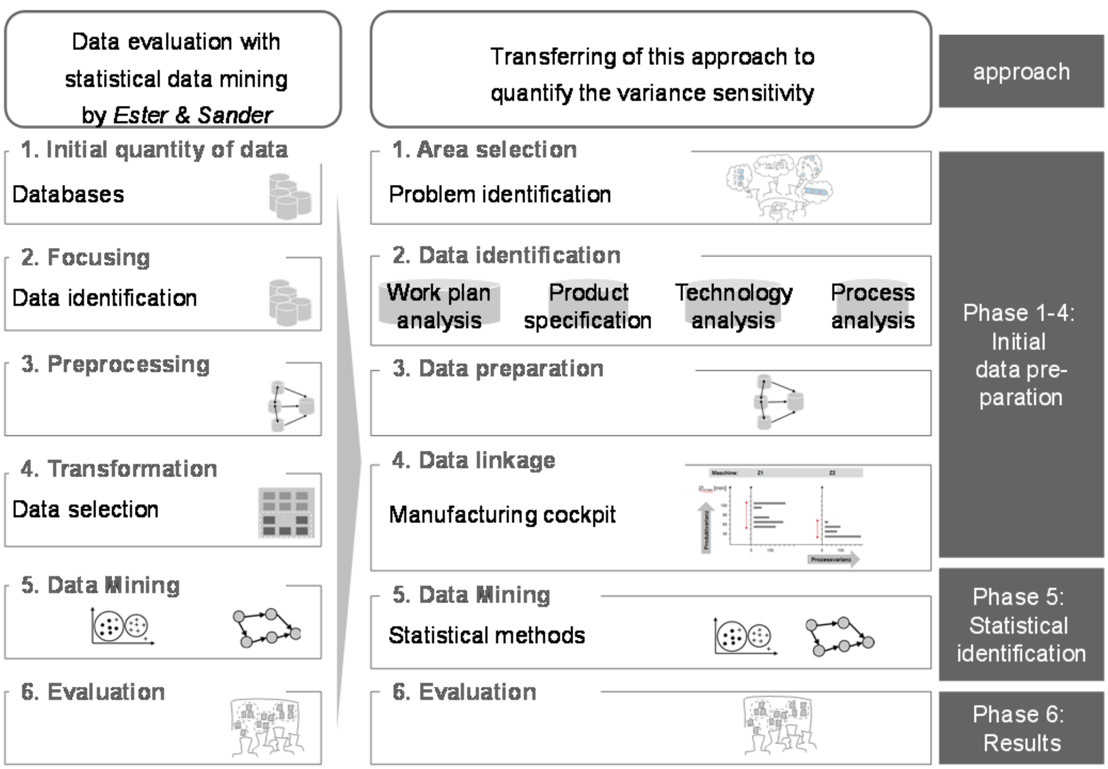


Fig. 13 Overview of the presented approach

In order to achieve this goal the named data sources have to be connected and relevant data information have to be extracted (phase 3). This step in the method depends on the structure and available information of the data sources. Since there is no general approach to derive the connection of the data sources we refer to chapter 5 where such a data preparation was carried out in an industry case. As a result of the data preparation phases a linkage between product features in their specific characteristics to the relevant production processes is derived in phase 4. Based on this data set it is possible to make a statement regarding which product feature, in which specific characteristic is produced on which process in which quantity (see Fig. 14). Phases 1 to 4 are solely preparation phases for the quantitative analysis of the variance sensitivity indicator stability in the following phase 5.

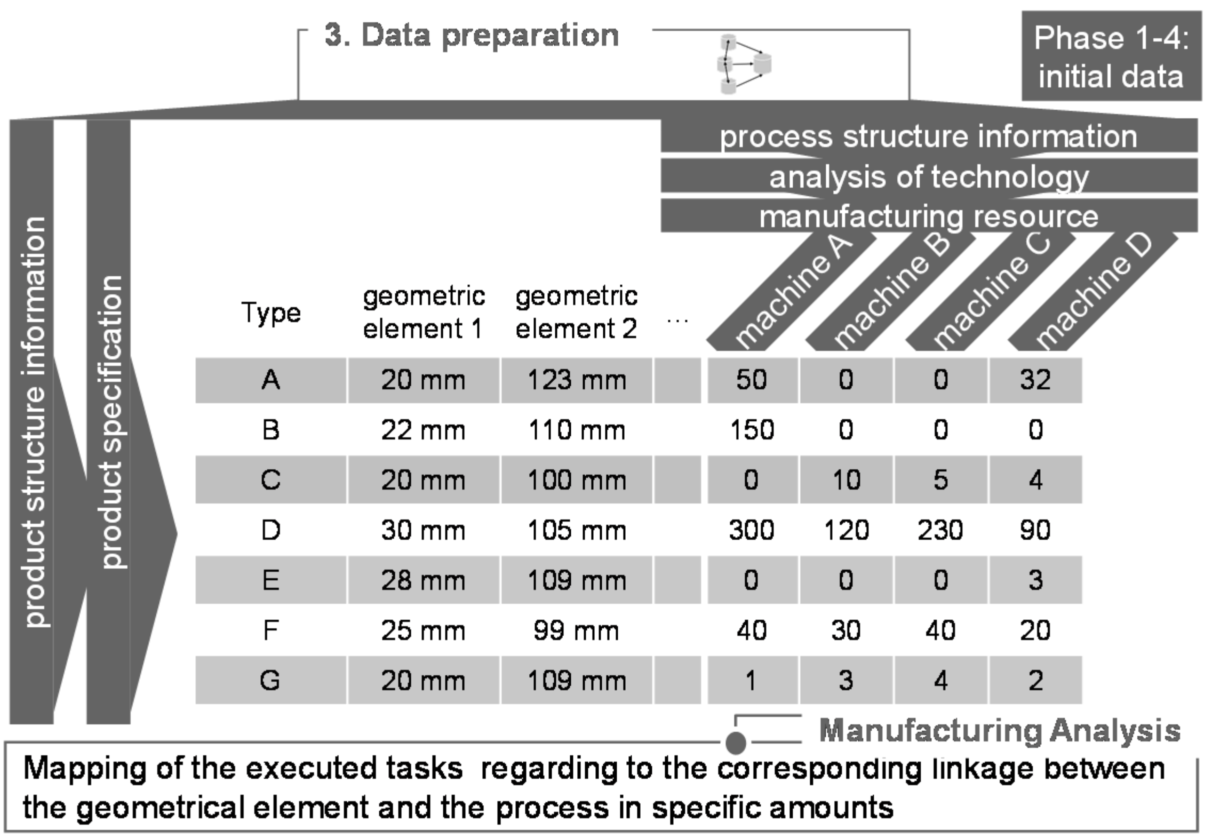
Phase 5: Statistical identification of the variance sensitivity indicator stability

In phase 5 of the proposed method the variance sensitivity indicator stability is described in a quantitative manner via a five step statistical analysis process. Fig. 15 gives an overview of these steps. In the following detailed descriptions these five steps of Phase 5 are presented. As a result of Phase 5 product or process features are identified for a set of product variants which lead to instable processes with regard to the variance sensitivity.

Phase 5 Step 1: Determining the similarity of product variants

Since the variance sensitivity compares the effects of product variants on manufacturing processes, it is necessary to identify a set of products which contains product variants. Therefore, the first step of the statistical analysis process compares products in order to identify product variants. In this connection a product variant is a component, which differs in at least one feature from comparable components but has at the same time a high degree of similarity with regard to its geometry [22, 34].

In the present paper we identify product variants from a large set of products via product features which manifest the outer appearances of the products. Since we focus on rotationally symmetric products main product features are the outer and inner diameter as well as the length of the product. After identifying product features a measure for the similarity of the products has to be derived. By comparing the geometry of the products via the distance of the product variants to each other it is possible to identify similar products. Each product variant is described by outer, inner diameter and its length in a quantitative way.



Type	geometric element 1	geometric element 2	…	machine A	machine B	machine C	machine D
A	20 mm	123 mm		50	0	0	32
B	22 mm	110 mm		150	0	0	0
C	20 mm	100 mm		0	10	5	4
D	30 mm	105 mm		300	120	230	90
E	28 mm	109 mm		0	0	0	3
F	25 mm	99 mm		40	30	40	20
G	20 mm	109 mm		1	3	4	2

Fig. 14 Linkage of product characteristics and manufacturing process

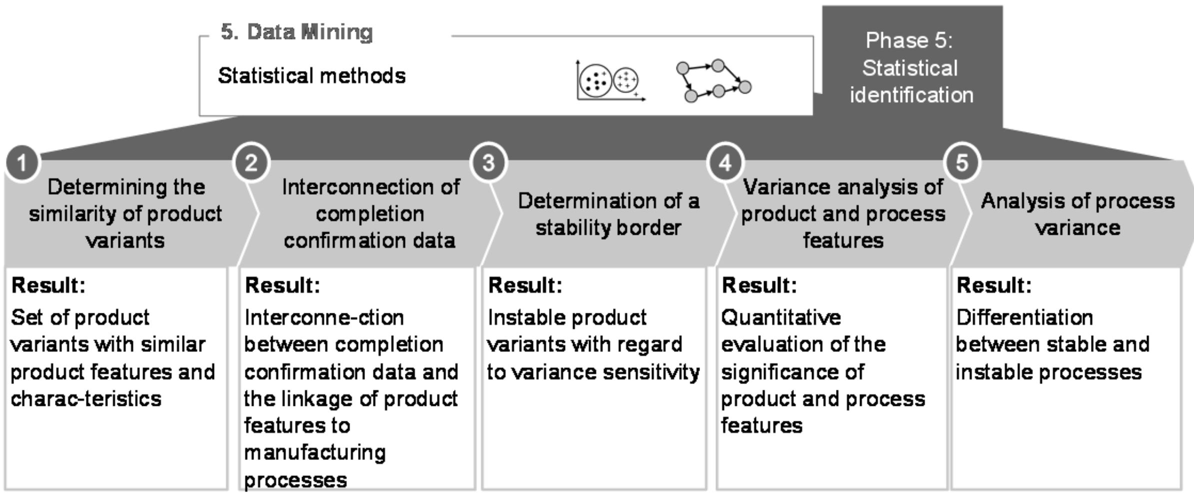


Fig. 15 Procedure of statistical analysis

In a three dimensional space each variant is represented by a single point. In other words, each point is a combination of outer, inner diameter and the length and therefore, describes one single product variant. The Euclidean distance between these points states the similarity of the examined products. A greater similarity between products requires a shorter distance between their respective points. By applying cluster analysis methods it is possible to generate clusters of data points of short distance to each other (see Fig. 16). Each cluster of data points describes a similar set of products and therefore, a set of product variants. The affiliation of one product variant to one cluster depends only on its product features' characteristic as well as the product features' characteristics of the cluster's other product variants. The result of step 1 is a set of product variants which are characterized by similar product features and characteristics.

Phase 5 Step 2: Interconnect completion confirmation data with the linkage of product features to manufacturing processes

In order to analyze the effect of the product variance on the variance sensitivity indicator stability the linkage between product features in specific characteristics to the relevant production processes has to be examined. As a result of the data preparation processes (see phase 1-4) it is known which product features are manufactured at which manufacturing processes in which quantity based on past production orders. These production orders have to be linked to completion confirmation data of the manufacturing processes to quantify the effects of product variance on manufacturing processes.

type	length	outside-Ø	inside-Ø	Cluster
1	42	180	117	2
2	40	180	117	2
3	40	180,4	117	2
4	42	180,2	132	2
5	31,4	180	115	3
6	34	126	84	1

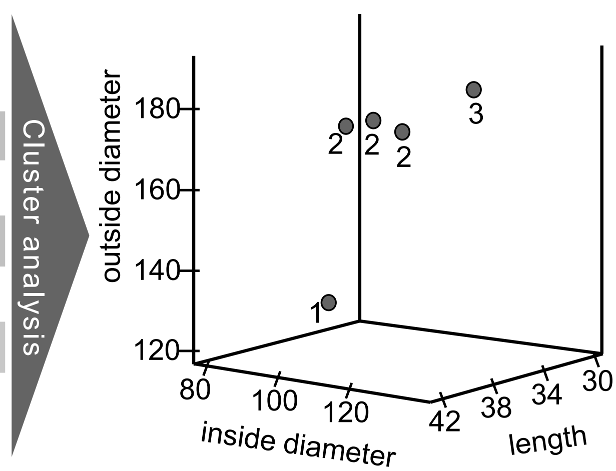


Fig. 16 Creation of product clusters based on geometrical product features

MES-systems serve as data sources. In the context of this paper process times, set up times, malfunction periods and reworking procedures are considered. As a result of step 2 an interconnection between completion confirmation data to the linkage of product features and manufacturing processes is derived.

Phase 5 Step 3: Determination of a stability border

In accordance to the definition of variance sensitivity the effect of product variance on manufacturing processes has to be examined. Therefore, the product variance with their specific product features represents independent variables, whereas completion confirmation data represents dependent variables. To define a criteria to distinguish between stable and instable production processes so called stability borders are determined via control ellipses.

Following formula (1) allows the determination of such control ellipses based on a set of data points by calculating $\chi^2_{1-\alpha}$ [23]:
$\chi^2_{1-\alpha}$ [65]:

$$\chi^2_{1-\alpha} = \frac{n}{1-\rho^2} \cdot \left[\left(\frac{\bar{x}_1-\mu_{01}}{\sigma_1} \right)^2 - 2\rho \left(\frac{\bar{x}_1-\mu_{01}}{\sigma_1} \right) \left(\frac{\bar{x}_2-\mu_{02}}{\sigma_2} \right) + \left(\frac{\bar{x}_2-\mu_{02}}{\sigma_2} \right)^2 \right] \qquad (1)$$

being

$\chi^2_{1-\alpha}$ = percentile function of the Chi square distribution
n = sample size
ρ = correlation coefficient
$\bar{x}_{1/2}$ = observed value
$\mu_{01/02}$ = mean value of the samples
$\sigma_{1/2}$ = standard deviation of the samples

Location, dimensions and gradient of these control ellipses are defined by the data set itself and have not to be defined prior to the data analysis. Based on stability borders, which are calculated by formula 1, two stability criteria are defined. First, a high variation of the completion confirmation data represents instable manufacturing processes. Processes with a high variation lead to unpredictable process behavior and as such to unstable processes. Stability borders incorporate this stability criterion via the height of the ellipses. Consequentially, manufacturing processes of certain product features, which lead to a high variance of the completion confirmation data, will be located outside the stability border in direct comparison of processes with lower process variance. Second, increases of completion confirmation data of certain processes are considered to be instable processes. In this case, not every increase of completion confirmation data has to be considered to be an instable process. Only if such increase is different of the process behavior of similar product features, it is reasonable to speak of instable processes. Via the gradient of the stability border it is possible to take the similarity of process behavior into account. The two main stability criteria are shown in Fig. 17. As an outcome of step 3 product variants are identified which lead to instabilities with regard to process times, set up times, malfunction periods and reworking procedures. In case of instable manufacturing processes it is of interest which product or process features have caused the instabilities.

Phase 5 Step 4: Variance analysis to identify product features with significant impacts

To identify the product features with significant impacts regarding variance sensitivity the main question is: Which product features are responsible for increases of certain command variables? Based on a three-step procedure an answer to this question is derived (see Fig. 18).

In accordance to the above three steps (4.1 to 4.3) an analysis of influential factors is carried out. To consider both process and product influential factors process and product clusters are generated. Product clusters are based on the described similarity of product variants. Similar technological restrictions as well as equal manufacturing processes are the used criteria for process clusters. By applying a variance analysis [8, 10] it is possible to determine which clusters describe differences in processing times. In the case of significance for the process cluster step 4.3 is obsolete and the analysis continues with step 5. If product clusters are characterized by significance step 4.3 has to be carried out (see Fig. 19).

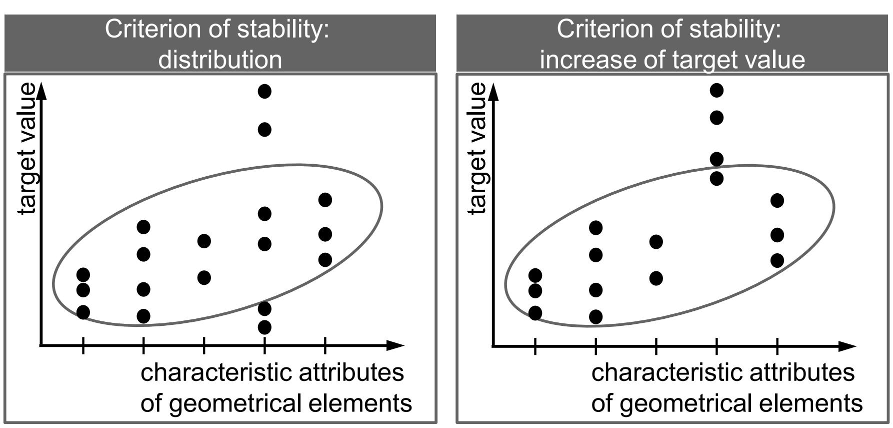


Fig. 17 Two possible cases as initial position for criterion of stability

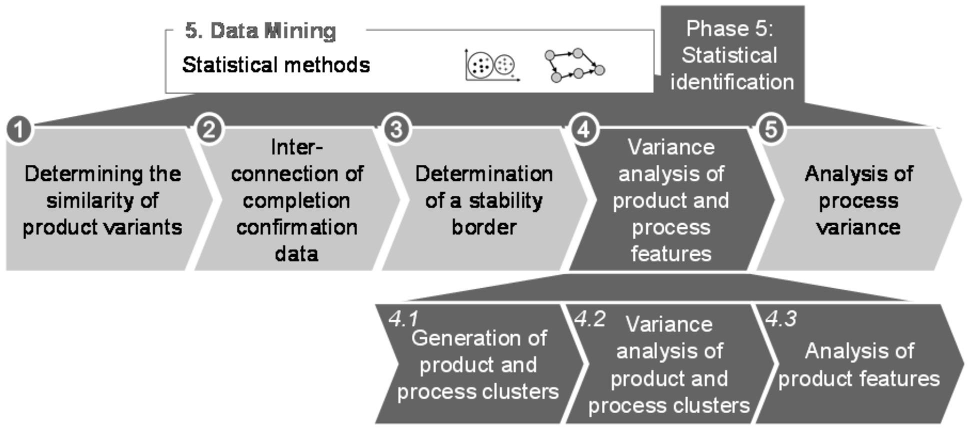


Fig. 18 Procedure of variance analysis

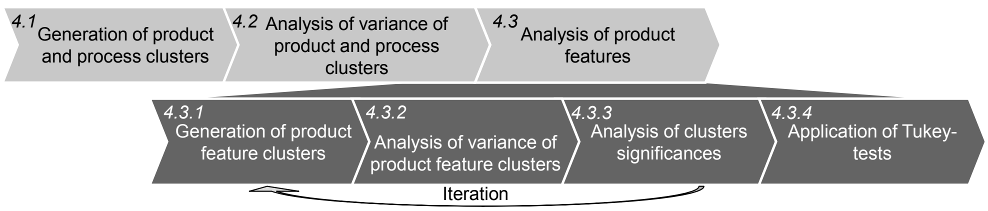


Fig. 19 Procedure of product feature analysis

In accordance to the above figure step 4.3 can be detailed in four substeps (4.3.1 to 4.3.4). First, clusters with regard to product features have to be generated. Those product features are of interest, which are produced within an instable process (see phase 5 step 3). Product features are randomly assigned to clusters. Via a variance analysis it is possible to determine which cluster of product features is characterized by a high significance. If no significant cluster is identified, a recombination of product features to clusters is necessary. Therefore, steps 4.3.1 to 4.3.3 are carried out in an iterative way until a significant cluster is found. By applying the Tukey-test it is possible to identify which specific characteristics of the significant product feature cluster have a significant impact on the command variables (step 4.3.4) [9]. A significant difference between two clusters is existent, if HSD_{γ} is smaller than the difference of the two mean values of the clusters (see formula 2) [23].

$$HSD_{\gamma} = \sqrt{\frac{MSE}{n}} \cdot q_{p,N-p;1-\gamma} \qquad (2)$$

Being

HSD_{γ} = least significance difference by Tukey with a significance value of γ

MSE = mean squared error

n = sample size

$q_{p,N-p;1-\gamma}$ = studentized range

After conducting step 4 it is known if identified instabilities are caused by specific process or product features. Furthermore, differences in command variables caused by certain product features are attributable to product feature characteristics.

Phase 5 Step 5: Analysis of process variance

To be able to analyze the process variance we propose the visualization of processing times of instable product variants via box-plots (see Fig. 20). These plots provide an overview of processing times of all utilized processes. Additionally, the plots show certain statistical characteristics of the processing times distributions. Based on these plots it is possible to identify instable processes of instable product variants.

As a result of step 5 an overview of the process variance is generated. Furthermore, process specific differences of the processing times distributions are analyzable.

Phase 6: Evaluation of the results

As the last step of the statistical analysis of the variance sensitivity indicator stability it is necessary to evaluate the achieved results (see Fig. 21). Goals of this phase are the confirmation or the refutation of identified instable product features or processes as well as the identification of not already considered product features. For the evaluation a survey of manufacturing and work preparation employees is recommended in order to consider both reasons for specific product-process-combinations as well as critical product features.

As a result of phase 6 it is known if identified instabilities are valid. Additionally, significant product features which were not included in the first analysis are identified.

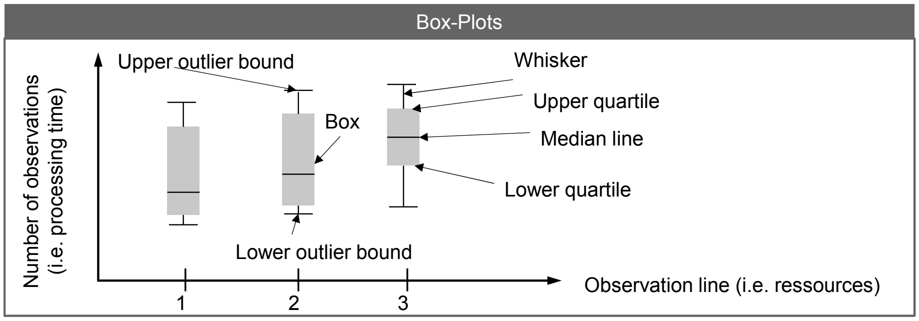


Fig. 20 Visualization of processing times of instable product variants (Source: [26])

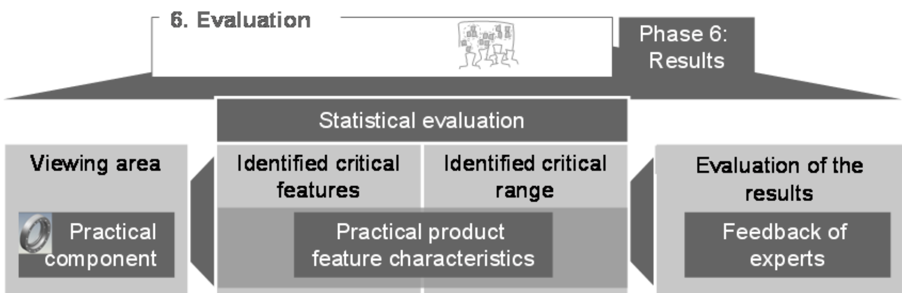
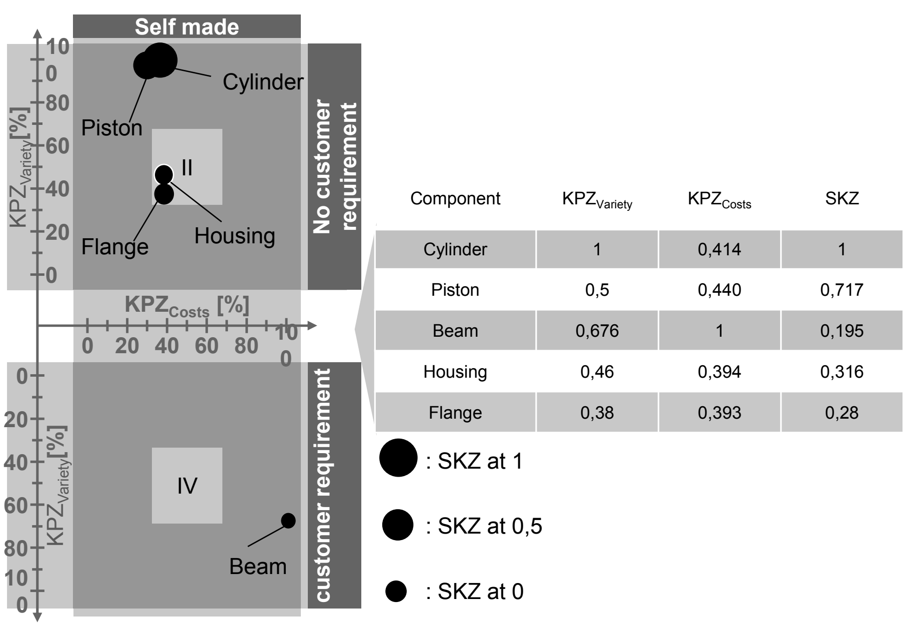


Fig. 21 Results of analysis

V. IMPLEMENTATION

Having a systematic and practical process to derive constituent features is future research and being developed at present within the research project “Design of innovative modular product platform and value added structures - GiBWert” (see www.gibwert.de), funded by the German Federal Ministry of Education and Research (BMBF). In order to validate the developed method for statistical identification of stability the method was applied in a small and medium-sized enterprise (SME) as part of the mentioned research project. The product portfolio of aforementioned company covers brakes and couplings for industrial application. A high product variance is reflected in 110 product classes with over 40.000 components. The production itself is organized as a job shop production with a inhomogenouos piece flow. The influence of product variance on manufacturing processes becomes apparent in over 20.000 different working plans [39].



Component	$KPZ_{Variety}$	KPZ_{Costs}	SKZ
Cylinder	1	0,414	1
Piston	0,5	0,440	0,717
Beam	0,676	1	0,195
Housing	0,46	0,394	0,316
Flange	0,38	0,393	0,28

Fig. 22 Identification of initial product set (Source: [3])

Implementation Phase 1 : Identification of initial product set

In the following chapter a series of hydraulically controlled brakes will be analyzed. The reasons for picking hydraulically controlled brakes are the big economical importance of this series for the company and their high rate of variant diversity. The series contains 382 different types of brakes (see Fig. 23: product level). On the level of components (see Fig. 23: component level) 112 beams, 116 pistons, 175 cylinders, 110 wafer type bodies, and 95 flanges can be identified. These data and the data below are based on the products/components produced from 2011 to 2013. The analysis of the variances $KPZ_{Variety}$ (complexity potential variety dimension) in accordance to the approach by Rudolf shows that the "cylinders" got a high diversity of variances and inhomogeneous distribution of the amount of production of those variances (see Fig. 22) [40].

Thus "cylinders" offer a big potential for standardization. The other components considered here show a medium diversity of variances. $KPZ_{Variety}$ (complexity potential costs dimension) is calculated based on formula 3 [18]:

$$KPZ_{Variety} = V_{abs} \cdot VP_{95\%} \quad (3)$$

Being

$KPZ_{Variety}$ = complexity potential (variety dimension)
V_{abs} = absolute number of product variants
$VP_{95\%}$ = 95%-variants percentile

Based on the KPZ_{Costs} number the impact of complexity costs is to be researched. The analysis of the calculated KPZ_{Costs} numbers shows that especially the component "beam" causes high complexity costs compared to the other components. On the other hand the components "cylinder", "piston", "housing" and "flange" show similar levels of complexity. KPZ_{Costs} is calculated based on the following formula 4 [32, 40]:

$$KPZ_{Costs} = MC \cdot \frac{CCP}{3} \quad (4)$$

being

KPZ_{Costs} = complexity potential (cost dimension)
MC = manufacturing costs
CCP = complexity cost profile

From the production point of view "cylinders" lead to the most common problems (SKZ = 1). The "pistons" are the second significant problematical component. They have a SKZ number of 0,717. The components "beam", "wafer type body" and "flange" have a potential of instability which is less than a third of one of the "cylinders". The analysis program MYSTAT has been used for the identification of possible instable components. Critical orders of a type of component, which are identified, will be considered on the basis of amount produced. SKZ is based on the following formulas:

$$SKZ_i = \frac{instability\ regarding\ processing\ times}{total\ amount\ produced} \quad (5)$$

being

SKZ_i = stability index for product component i

and

$$SKZ_{i,scaled} = \frac{SKZ_i}{SKZ_{i,max}} \quad (6)$$

As it can be seen from this initial analysis especially the component group "cylinders" should be observed closer. Its diversity of variance as well as its manufacturing reveal the biggest potential.

Implementation Phase 2: Identification of relevant data sources

Product-sided the analysis considers information about the structure of the product and detailed product specifications. Bill of materials of the components enable the breakdown of the manufacturing order from raw parts to half-finished parts to finished parts. As a result the whole manufacturing history can be taken into consideration. Within the product specification a CAD product model analyzer allows the generation of a database, which contains the quantitative description of product features. Thus a differentiation of product variants using geometrical features is possible as shown in Fig. 23.

Process-sided the analysis considers working plans, a technology database and production orders. Working plans offer detailed information about the work to be done within every manufacturing step. This data source enables to establish a link between geometrical features to their respective manufacturing processes. The technology database contains the manufacturing processes of each manufacturing resource, the limits of the installation space and the geometrical features which can be produced by the manufacturing process. The production orders of the observed company provide data with regard to which machine produced which quantity of product variants in the past.

Implementation Phase 3 : Preparation and linkage of data sources

In the next step of the statistical analysis those product types which are to be studied will be matched to their working plans and bill of material using their material number. On the basis of the analysis of the bill of materials, additional material numbers are generated in order to be able to map the whole manufacturing history of the respective product types. Those material numbers serve as an additional input for the analysis of the working plan. Within that analysis the geometric features, which can be matched to specific manufacturing processes, are detected. The generation of the technology database considers the minimal and maximal deviation of the producible product types, possible manufacturing processes of the corresponding manufacturing resource and assignment of geometrical features to manufacturing processes. Based on this analysis appropriate manufacturing resources for manufacturing the different product variants are prescribed. Appropriate manufacturing resources characterized by two restrictions.

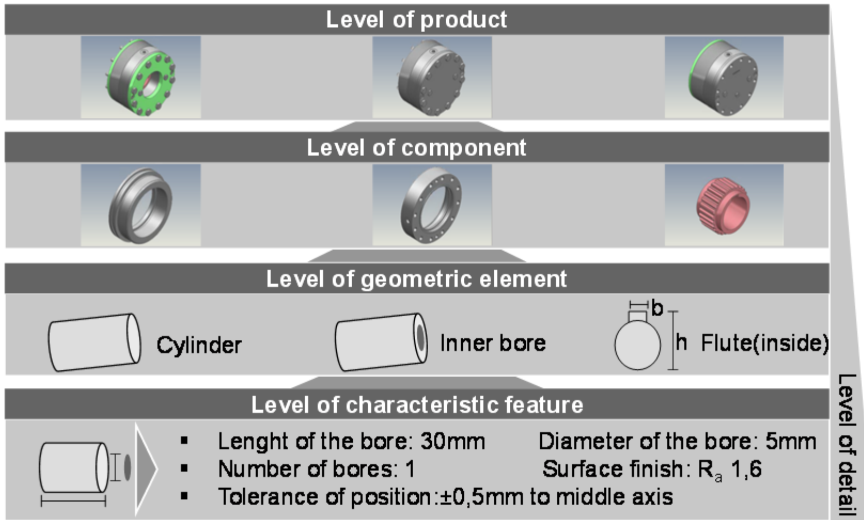


Fig. 23 Level of abstraction within the product analysis

First is that the deviation of the product variant does not exceed the restrictions given through the installation space of the manufacturing resource. The second restriction is that necessary manufacturing processes for manufacturing specific geometrical features are available for a manufacturing resource. Executed steps of production are considered by analyzing the production orders. Only if the numbers of process, working plan and material coincide and the installation space is not exceeded, the identified geometric elements are assigned to the specific manufacturing step of a production order. As a result of the proposed data flow model (see Fig. 24) it is known which product feature of a product variant in their specific characteristics is manufactured on which process in which quantity.

Implementation Phase 4: Aggregation and Visualization of relevant data

Upon completion of the necessary data flow model, the regenerated data is aggregated and visualized. This includes the description of the product variety as well as process variety to provide a basis for the evaluation of the variance sensitivity. Product variation is to analyze on the level of product features in their specific characteristics. Furthermore the process variance of the manufacturing resources has to be included on an individual machine level. In the context of a clear and convincing representation, the manufacturing cockpit is presented in Fig. 25, which combines the described product and process variance in an overview.

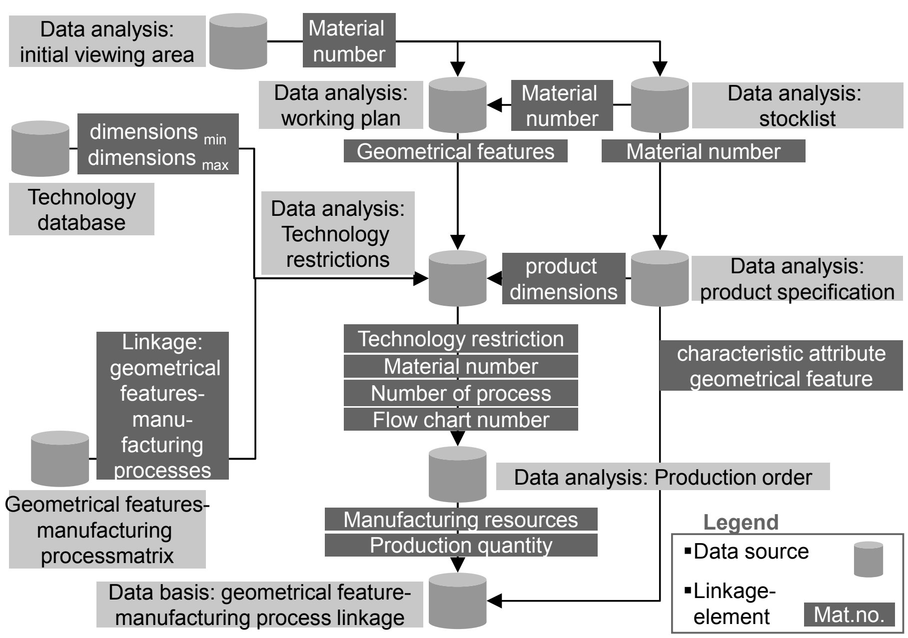


Fig. 24 Data model of linkage product feature and manufacturing process

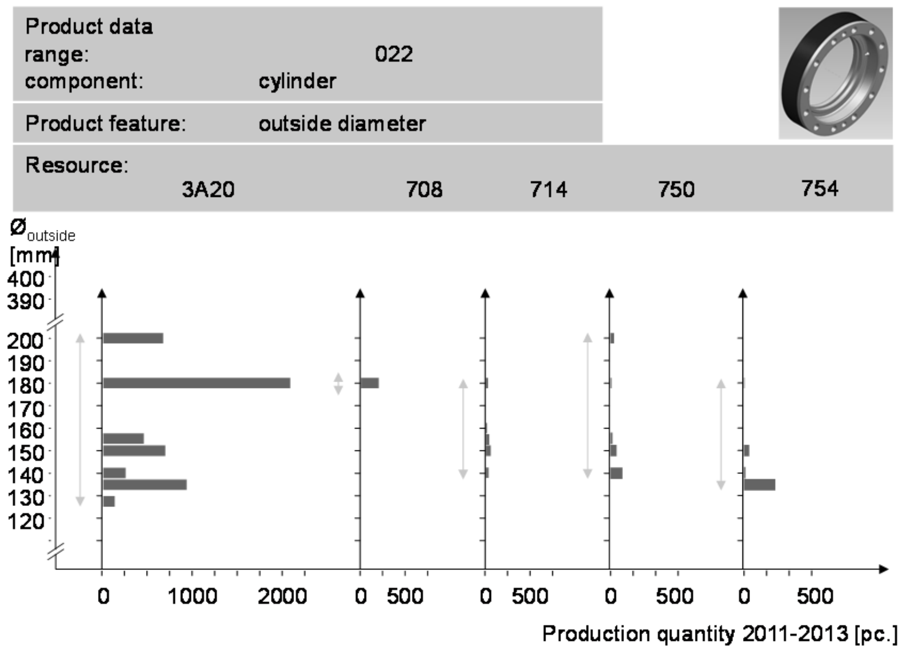


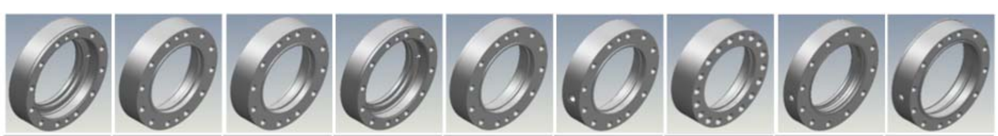
Fig. 25 Manufacturing cockpit

The y-axis of the manufacturing cockpit describes the product variance with regard to the product features in their specific characteristics.

On the x-axis of the manufacturing cockpit the production quantity for an analysis period for specific product features is imaged. The analysis of the variance sensitivity requires the consideration of process variance for the analysis of product-process interdependencies. Therefore, resource specific x-axes are introduced, so that the production quantity of each manufacturing resource is mapped individually. From the manufacturing cockpit of the product component cylinder in Fig. 25 one can see that the manufacturing resource 3A20 is proportionally often used for the manufacturing of all analyzed cylinders. Additionally, the variance of the manufactured product features is the highest for this manufacturing resource.

Implementation Phase 5: Statistical Identification of variance sensitivity

The statistical analysis was carried out for all cylinder product variants of the chosen product class. In the following the five introduced analysis steps are applied in the case study.



Variant	A	B	C	D	E	F	G	H	I
outside-Ø [mm]	180,4	180	180	180,4	180	180	126	180	180,2
inside-Ø [mm]	117	117	117	117	117	117	84	115	132
length [mm]	40	42	42	40	40	40	34	31,4	42
#sealing surfaces	1	1	1	1	1	1	1	0	2

Fig. 26 Similarity of products ”cylinders” regarding geometrical dimensions

Implementation Phase 5 Step 1: Similarity of product variants

Due to the classification of the cylinders in size classes considering their geometrical dimensions, a similarity classification of the examined cylinders is already existent. Fig. 26 shows that the classification of the cylinder variants in size classes factors the similarity of their geometrical dimensions, as well as their outer appearance in. Consequently, the classification by size classes leads to a similarity classification of the cylinders, so that an initial determination of their similarity is not necessary.

Implementation Phase 5 Step 2: Interconnect completion confirmation data with the linkage of product features to manufacturing processes

After stating the basic similarity of the cylinders, the analyzed production quantities of the manufacturing cockpit have to be linked with completion confirmation data. This link includes the assignment of processing times to identified product features in their specific characteristics and the respective processes. In the context of the case study semi-automated recorded feedback data of the processing times of production orders are used.

Implementation Phase 5 Step 3: Determination of the stability border

For the determination of the stability border of the cylinder, the product feature length will be used to differentiate between the examined cylinder variants. The stability border shown in Fig. 27 describes by its slope an increase of the processing times of the cylinder variants in dependency of their length. For the stability border of the cylinders a significance level of α = 10 % is chosen. The location of the measured points and the size and orientation of the stability border suggest that cylinder variants with a length of 42 mm lead to unstable increases in processing times with regard to the variance sensitivity indicator stability. Although the cylinder examined have a high similarity, this increase is evident. It is also evident from the stability edge, that there are product variants, which have a low processing time in spite of its length of 42 mm. The next analysis step is therefore to determine statistically which product or process features are responsible for the identified instability with regard to the processing time.

Implementation Phase 5 Step 4: Variance analysis to identify product features with significant impacts

Fig. 28 shows the four steps within step 4.3.

Visualization of stability border

Implementation Phase 5 Step 4.1: Generation of product and process clusters

In accordance to the developed analysis steps product and process clusters have to be generated.

The product feature outside diameter, inside diameter, length and number of sealing surfaces are examined for the cluster analysis with the program SPSS.

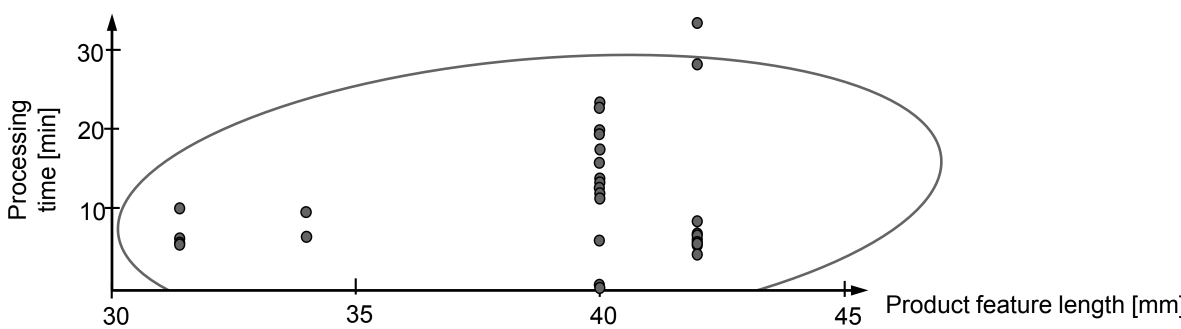


Fig. 27

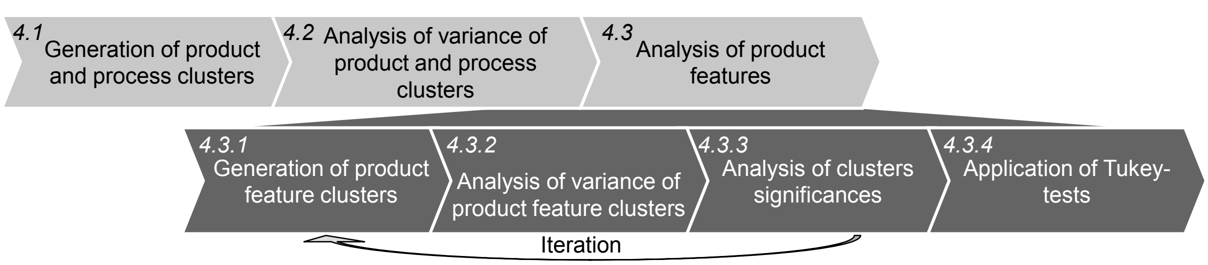


Fig. 28 Overview of the analysis steps of Phase 5 step 4

Variant	outside-Ø [mm]	Inside-Ø [mm]	length [mm]	# sealing surfaces	cluster (Akaike)	cluster (Bayes)
1	126	84	34	1	3	2
2	180,2	132	42	2	4	1
3	180	115	31,4	0	2	2
4	180	117	40	1	1	1
5	180	117	42	1	1	1
6	180,4	117	40	1	1	1

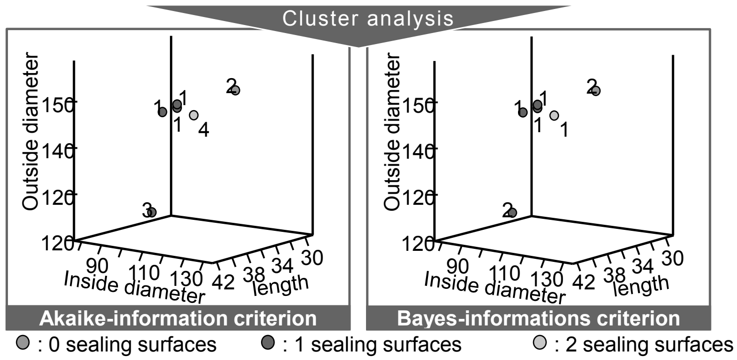


Fig. 29 Product cluster analysis

In contrast to the product features outside diameter, inside diameter and length which are continuous variables, the product feature number of sealing surfaces is a categorical variable, because its characteristic values can take only integer values. The product side cluster assignments are shown in Fig. 29. By using a log-likelihood distance measure both categorical and continuous variables can be taken into account in the cluster analysis. The criterion for this cluster formation is not the Euclidean distance between the dimension values of the product features, but the probability distributions of the single product features [23]. Furthermore, the Akaike information criterion is chosen, because it leads to the highest resolution of the allocation of product variants into clusters.

The result of the process cluster analysis are two clusters, where the first cluster consists out of the manufacturing resource 3A20, and the second cluster is made up out of additional manufacturing resources. Both product and process clusters have been formed with the help of the two-step cluster analysis of the SPSS program.

Implementation Phase 5 Step 4.2: Analysis of Variances of product and process clusters

The variance analysis of the product and process clusters is applied by the significance level of α = 0,05 (step 4.2). The significance value of the product cluster is 0,006 and the significance value of the process cluster is 0,083. Consequently, the product cluster contains a high significance, whereas the process cluster is considered to be insignificant. Thus, the instability of the processing time is attributed to the cylinder variety. According to the developed concept of variance sensitivity analysis the identified product effect has to be specified in the next step. To this end, the considered product feature outside, inside diameter, length and number of sealing surfaces are analyzed in the following.

Implementation Phase 5 Step 4.3: Analysis of product features

Fig. 28 shows the four steps within step 4.3.

Implementation Phase 5 Step 4.3.1: Generation of product feature clusters

For the analysis of product features two product feature clusters are generated, wherein the assignment of product features to their respective clusters is chosen randomly. As the starting point of the product feature clustering the outside diameter is combined with the number of sealing surfaces and the inner diameter is combined with the length.

Two-step analysis for both our product feature clusters leads to three clusters (see Fig. 30).

Implementation Phase 5 Step 4.3.2: Analysis of variance of product feature clusters

The next step is to verify whether both formed product feature clusters are regarded as significant. As a result of analysis of variance both clusters are considered to be significant because for a significance level of α = 0,05 they show significance values of 0,000. Consequently, it is not possible at this point to attribute the rise of the processing times to a specific product feature cluster.

Implementation Phase 5 Step 4.3.3: Analysis of clusters significances

Since both clusters have a α-value of below α = 0,05 it is not possible to assign instabilities to a specific product feature cluster.

1st iteration

outside-Ø [mm]	# sealing surfaces	cluster	inside-Ø [mm]	length [mm]	cluster
126	1	3	84	34	3
180,2	2	2	132	42	1
180	0	2	115	31,4	2
180	1	1	117	40	1
180	1	1	117	42	1
180,4	1	1	117	40	1
significance		0,000			0,000

random combination

2nd iteration

outside-Ø [mm]	inside-Ø [mm]	cluster	# sealing surfaces	length [mm]	cluster
126	84	2	1	34	1
180,2	132	1	2	42	3
180	115	1	0	31,4	2
180	117	1	1	40	1
180	117	1	1	42	1
180,4	117	1	1	40	1
significance		0,544			0,000

exclude the insignificant clusters

3rd iteration

	#sealing surfaces	cluster	length [mm]	cluster
	1	1	34	2
	2	3	42	1
	0	2	31,4	2
	1	1	40	1
	1	1	42	1
	1	1	40	1
significance		0,001		0,544

Fig. 30 Procedure of variance sensitivity analysis of a cylinder regarding shape elements

Iteration of Phase 5 Steps 4.3.1 to 4.3.3

Consequently, it is not possible at this point to attribute the rise of the processing times to a specific product feature cluster. For this reason, another random combination of the four product features, cluster generation as well as a variance analysis of the clusters are carried out. As part of this analysis the outer and inner diameter and the length and number of sealing surfaces are combined in clusters (see Fig. 30). The variance analysis provides as a result that at the significance level of $\alpha = 0,05$, the outer diameter-inner diameter cluster with a significance value of 0,544 is not significant. In contrast, the cluster comprising the length and the number of sealing surfaces is significant with a significance value of 0,000. Consequently, the increase in the processing times is with high probability attributable to the length and number of sealing surfaces cluster. Accordingly, the product feature outer and inner diameter are to exclude for the further analysis. In order to analyze whether the product feature length or number of sealing surfaces shall be identified as variance-sensitive characteristic, clusters of these product features are formed (see Fig. 30). As a result of a final analysis of variance of the product feature clusters the number sealing surfaces cluster is regarded as significant with a significance value of 0,0001 on the significance level $\alpha = 0,05$. In contrast, the product feature cluster length has a significance value of 0,544, so this cluster has to be regarded as insignificant.

Implementation Phase 5 Step 4.3.4: Analysis of clusters significances Application of Tukey-tests

As a result of the prior analyses the increase in processing times is attributable to the product feature number sealing surfaces. The in SPSS implemented Tukey-test returns as a result that the cluster 3 of the product feature cluster number sealing surfaces is significantly different on the significance level $\alpha = 0,05$ in comparison to the clusters 1 and 2. From this result, it can be concluded that cylinder variants having two sealing surfaces, lead to significant differences in processing times compared to similar cylinder variants.

Implementation Phase 5 Step 5: Analysis of the process variance

In the fifth step it is necessary to analyze the difference between critical elements with regard to the manufacturing processes. Because of too few production orders, the manufacturing processes of the cylinder variants with zero, one and two sealing surfaces are compared directly (see Fig. 31). The average of process time of the cylinder variants with null head gasket is 7,43 minutes, cylinder variants with one sealing surface lead to an average of 10,52 minutes. A big difference is apparent for cylinder variants with two sealing surfaces. Manufacturing this product feature two times takes 30,7 minutes on average. By this comparison the conclusion can be drawn that cylinder variants with two sealing surfaces are responsible for instabilities in manufacturing processes. The manufacturing resources 3A20, 708, 714, 750 and 754 represent machines which produce cylinder types with null or one head gaskets. The critical cylinder type is shown by number 708 (critical variant). Independent of the different manufacturing resources the working times of stable cylinder variants have a homogenous dispersion.

In the opposite the working time of the instable cylinder variant differs to stable cylinders. A direct comparison between stable and instable cylinders emphasizes that the increase in working time comes to 200%. On the basis of the analysis of process variance it is shown that the manufacturing of two sealing surfaces results in instability with regard to the process time.

Implementation Phase 6 : Evaluation

Interviews of the employees, who operate the manufacturing resource 708 have shown that roller-burnishing of two sealing surfaces is much more time-consuming than the roller-burnishing of one or sealing surface (see Fig. 32). Reasons for this time increase are the required dimensional tolerances of the cylinder product features. The dimensional tolerance of the first sealing surface does not lead to additional process times. But the second area results in problems regarding the dimensional accuracy of the sealing surfaces to each other. This problem requires additional manufacturing roller-burnishing processes, which directly increase the process time.

The identified instability caused by the product has to be validated. In this context there are two main questions:

- Why does the process time increase in a large way for the manufacturing of cylinders with two sealing surfaces?
- Is it possible to achieve a stable level of process time by reducing the number of sealing surfaces?

By conducting interviews it is shown that the product feature number of sealing surfaces is responsible for increasing process times, if the characteristic of the product feature is two. In the context of the analysis of the variance sensitivity these increases of process time have been compared with other similar cylinder variants. In this way instability with regard to the variance sensitivity could be proved. Consequently an instability caused by the product exists in relation to variance sensitivity. The main hypothesis of this paper states that product variance has an impact on the stability of manufacturing processes. By applying the developed approach in a case study it was shown that a quantitative analysis of the variance sensitivity indicator stability is possible. Therefore, the main hypothesis of this paper is confirmed and the approach's aim reached. Future work will focus on using results of the quantitative analysis concerning the variance sensitivity to derive constituent features (see Fig. 33).

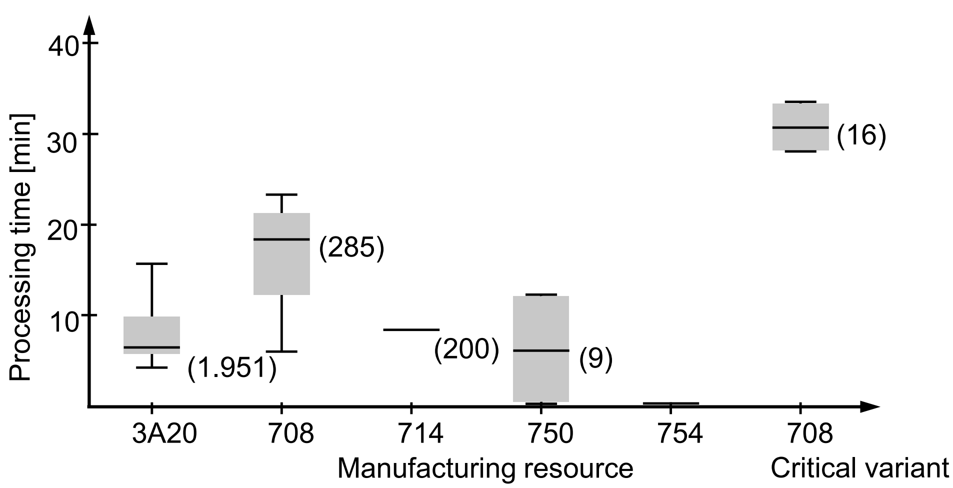


Fig. 31 Visualization of critical product features and linkage to manufacturing processes

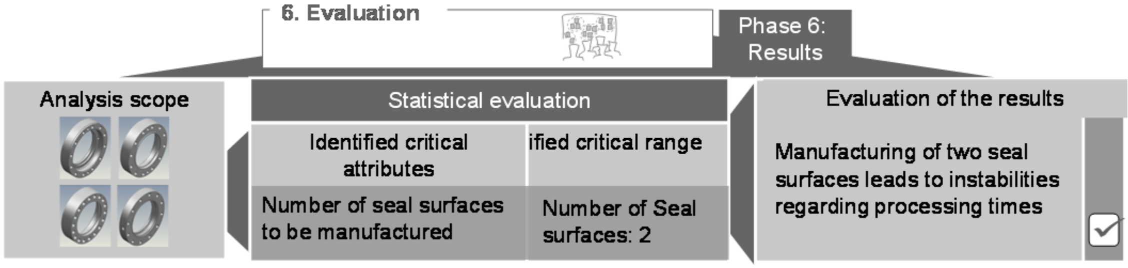


Fig. 32 Evaluation of the achieved results

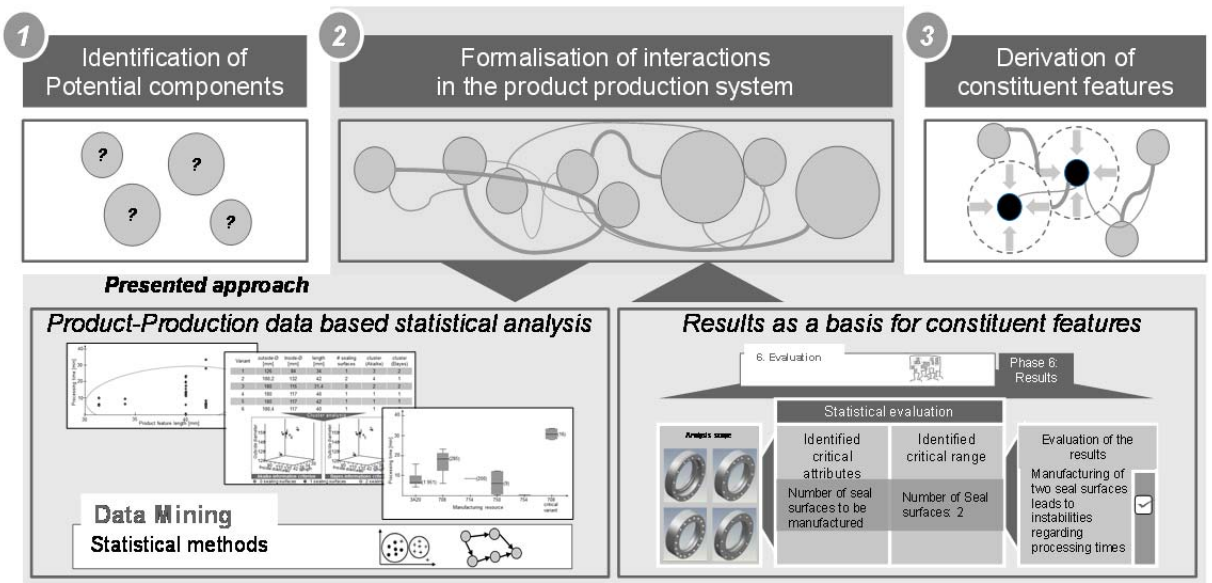


Fig. 33 Results of approach as an input for deriving constituent features

VI. CONCLUSION AND OUTLOOK

Highly customized products have led to high product and process complexity causing a reduction of cost effectiveness of manufacturer of small batch series of the machinery and plant engineering. Today's product design and IT-tools reduce this complexity insufficiently and potentials in administration and manufacturing are not fully lapped. The presented approach is integrated within a method to develop a modular product platform based on constituent features. Constituent features describe standards in product design as well as in production processes and enable cost potentials to increase cost effectiveness. To derive these constituent features it is necessary to identify the cost influence of product design on manufacturing processes. Existing approaches do not precisely identify and quantify this influence, which is defined as the variance sensitivity. The concept is based on data mining approaches using statistical methods to analyze product and manufacturing data. The concept implies a six step procedure to identify the variance sensitivity indicator stability. Within this approach processing times of slightly similar products are analyzed to identify critical product features that cause instable manufacturing processes. Within the project "Design of innovative modular product platform and value added structures - GiBWert" (see www.gibwert.de), funded by the German Federal Ministry of Education and Research (BMBF), a method to systematically link product and process data will be implemented. The aim of this project is a constant product and process tracking system, which realizes complexity restrictions in the product development process. A fundamental part of the research project is to develop a method of systematically detecting and evaluating the variance sensitivity of manufacturing processes. The challenge of future research work is to combine and aggregate the results of the three different variance sensitivity indicators and convert the findings to a mathematical function. All in all this expression of the variance sensitivity will be used to set product feature standards that allow an economically manufacturing alongside the desired product variety. At present the approach presented within this research project is used to execute automated evaluation and generate the data base for the derivation of product standards at small business of the machinery and plant engineering.

ACKNOWLEDGMENTS

The research and development project “Design of innovative modular product platforms and value added structures- GiBWert” is funded by the German Federal Ministry of Education and Research (BMBF) within the Framework Concept ”Research for Tomorrow’s Production” and managed by the Project Management Agency Karlsruhe (PTKA). The main research objective is to develop a product development process for modular product platforms and a holistic method to evaluate possible design scenarios. The author is responsible for the contents of this publication.

REFERENCES

[1] Bauhoff, F., G. Schuh, S. Kompa, F. Gläsner and E. Eicken, “Self-optimizing planning processes“, wt-online, pp. 431-434, 06/2012.
[2] Beckert, B. and W. Hudetz, “Stand und Potenzial produktnaher Datenverarbeitung“, PPS Management, pp. 35–39, 2002.
[3] Berry, W., L. and C. Martha, “Manufacturing flexibility: methods for measuring the impact of product variety on performance in process industries”, in Journal of Operations Management, 1999.
[4] Blecker, T. and G. F. Hardcover, “Mass Customization: Challenges and Solutions“, International Series in Operations Research and Management Science, pp.190-192, 2006.
[5] Bozarth, C. C.,D. P. Warsing, B. B. Flynn and E. J. Flynn, “The impact of supply chain complexity on manufacturing plant performance“, in Journal of Operations Management 27 (1), pp. 78–93 , 2009.
[6] Brecher, C. ; Integrative Production Technology for High-Wage Countries, Springer. Berlin, 2011.
[7] Cai, Y., A. Nee and W. Lu, “Platform differentiation plan for platform leverage across market niches, CIRP Annals“, in Manufacturing Technology 1, pp. 141-144, 2008.
[8] Christensen, R., “Analysis of Variance, Design, and Regression: Applied Statistical Methods“, 1996.
[9] David, C. L.; Statistics: Concepts and Applications for Science, 2004.
[10] Duncan, A. Quality control and industrial statistics, 4th edition, Homewood, III R.D. Irwin, 1974
[11] ElMaraghy, H. A.; Changeable and reconfigurable manufacturing systems. London, 2009.
[12] Ericsson, A. and G. Erixon, “Controlling design variants – Modular product platforms, Society of Manufacturing Engineers“, ASME Press, Dearborn Mich (NY), 1999.
[13] Ettlie, J. E., “Integrated Design“, Grundlagen der Produktgestaltungsansätze 47, p. 33, 1997.
[14] Fisher, M., R. Kamalini and K. Ulrich, “Component Sharing in the Management of Product Variety: A Study of Automotive Braking Systems“, Management Science, pp. 297–315, 1999.
[15] Fogliatto, F., G. Da Silveira and D. Borenstein, “The mass customizaation decade“, International Journal of Production Economics, pp. 14-25, 2012.
[16] Ghosh, A., S. Dehuri and S. Ghosh, “Multi-Objective Evolutionary Algorithms for Knowledge Discovery from Databases“, Berlin, 2008.
[17] Halevi, G. ; Process and operation planning Kluwer Academic Publishers. Dordrecht, 2003.
[18] Herstatt, C., 2000, “Management von technologie-getriebenen Entwicklungsprojekten“, Arbeitspapier Nr.5, Technical University Hamburg-Harburg, 2000.
[19] Hopp, W. J. and M. L. Spearman; Factory physics. Irwin McGraw-Hill, Boston, 2000.
[20] Kamalini, R., “Managing Product Variaty. An integrative review and research Directions“, Production and Operations Management, pp. 79–101, 2003.
[21] Lang, S.; Komplettbearbeitung rotationssymmetrischer Werkstücke für die Verfahrensfolge Drehen, Laserstrahlhärten, Schleifen. Essen, 1998.
[22] Lingnau, V., “Variantenmanagement - Produktionsplanung im Rahmen einer Produktdifferenzierungsstrategie“, Berlin University, 1994.
[23] Mardia, V., J. Kent and J. M. Bibby ; Multivariate Analysis, Academic Press, London, 1979.
[24] Martin, M. and I. Kosuke, “Design for variety – A methodology for developing product platform architectures“, ASME Design Engineering Technical Conferences, Baltimore, 2000.
[25] Mittal, S. and F. Frayman, “Towards a generic model of configuration tasks“, 11th International Joint Conference on Artificial Intelligence, Detroit, 1989.
[26] Montgomery, D. ; Design and analysis of experiments, Eighth edition. 2013.
[27] Nevins, J. L., D. E. Whitney, T. L. De Fazio,”Concurrent design of products and processes: a strategy for the next generation in manufacturing”, 1989.
[28] Opitz, H.; Werkstückbeschreibendes Klassifizierungssystem. Essen, 1966.
[29] Pahl, G. and W. Beitz; Engineering Design: A Systematic Approach. Berlin, 1999.
[30] Pimmler, T.U., “Integration Analysis of Product Decompositions“, ASME Design Theory and Methodology Conference, Minneapolis, 1995.
[31] Rathnow, P., J.; Integriertes Variantenmanagement. Göttingen, 1993.
[32] Rudolf, S.; Produktionsgerechte Baukastengestaltung. Aachen University, 2013.
[33] Saenz de Ugartea, B., A. Artibab and R. Pellerina, “Manufacturing execution system – a literature review in Production Planning and Control“, The Management of Operations, Volume 20, pp. 525-539, 2009.
[34] Schuh, G., J. Arnoscht, A. Bohl and C. Nußbaum, “Integrative assessment and configuration of production systems“, in CIRP Annals - Manufacturing Technology, 2011.
[35] Schuh, G., J. Arnoscht, S. Rudolf and M. Schiffer, “Lean Innovation with Commonality Models, Proceedings of the 4th ISPIM Innovation Symposium“, Wellington, 2011.
[36] Schuh, G. and M. Grawatsch, “TRIZ-based technology intelligence, International Association for Management of Technology“ ,13th International Conference on Management of Technology, 2004.
[37] Schuh, G., T. Potente, S. Fuchs and C. Thomas, “Effects of production structure and production control to logistic targets, Proceedings of the APMS 2011 International Conference - Advances in Production Management Systems“, University of Stavanger, Stavanger/ Norway, 2011.
[38] Schuh, G., T. Potente, C. Thomas and S. Schmitz, “Designing rotationally symmetric products for multi-variant mass production by using production-technical solution space“, Advances in Production Management Systems APMS 2012, Rhodes, Greece, 2012.
[39] Schuh, G., T. Potente, C. Thomas, S. Schmitz and C. Covello, “Development of Design Principles for an integrated product and process development apporach for rotationally symmetric products in Challenges for sustainable operations“, 22nd International Conference on Production Research, Brazil, 2013.
[40] Schuh, G., S. Rudolf, J. Arnoscht, “Production-Oriented Modular Platform Design“, International Conference on Competitive Manufacturing COMA, Stellenbosch, 2013.
[41] Schuh, G, V. Stich, T. Brosze, S. Fuchs, C. Pulz, J. Quick, M. Schürmeyer and F. Bauhoff, “High Resolution Supply Chain Management - Optimised Processes based on Self-Optimizing Control Loops and Real Time Data“, 2011.
[42] Schuh, G., C. Thomas, S. Fuchs and T. Potente, “Interactive visualization in production control, Future Trends in Production, Innovation and Technology Management”, pp. 203-211, 2011.
[43] Shao, X.Y., Z. H. Wang and P. G. Feng, “Integrating data mining and rough set for customer group-based discovery of product configuration rules“, International Journal of Production Research, pp. 2789-2811, 2006.
[44] Spur, G. and F. Krause; Das virtuelle Produkt. Management der CAD-Technik. München, 1997.
[45] Stotz, M.; Adaptive Segmentierung von Tiefenbildern für die 3-D-Objektlageerkennung auf Basis von kombinierten regelgeometrischen

Elementen. Institute for Control Engineering of Machine Tools and Manufacturing Systems, Stuttgart University, pp. 31- 32, 2011.
[46] Thonemann, U., W. and J. R. Bradley, “The effect of product variety on supply-chain performance“, in European Journal of Operational Research, pp. 548–569, 2002.
[47] Tu, Y. L., S. Q. Xie and R. Y. K. Fung, “Product development cost estimation in mass customization“, in IEEE Transactions on Engineering Management 54, pp. 29-40, 2007.
[48] Weinert, K.; Spanende Fertigung. Vulkan Verlag, Essen, 2001.
[49] Wheelwright, S. C. and K. B. Clark, Revolutionizing Product Development, in Free Press, p. 14, 1992.
[50] Wiendahl, H. H. A. ElMaraghy, P. Nyhuis, M. F. Zäh, H. Wiendahl, N. Duffie et al., “Changeable Manufacturing - Classification, Design and Operation“, CIRP Annals - Manufacturing Technology, pp. 783–809, 2007.
[51] Zha, X. F., R. D. Sriram, M. G. Fernandez and F. Mistree, “Knowledge-intensive collaborative decision support for design processes: a hybrid decision support model and agent“, in Computers in Industry, 2008.
[52] Zhang, M. and M. M. Tseng, “A product and process modeling based approach to study cost implications of product variety in mass customization“, in IEEE Transactions on Engineering Management 54, pp. 130-144, 2007.