MULTILEVEL PROCESS DIMENSIONING REGARDING CONTRARY TARGET VALUES

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Abstract

The result of a machining process is determined by input, process and output parameters. The adjustment and optimisation of these parameters regarding technological, economic and ecological criteria is defined as process dimensioning. Local process optimisation can be considered as state-of-the-art in dimensioning manufacturing processes. Technological interfaces as well as multi-criteria characteristic of decisions in manufacturing are often not considered. However, this type of configuration is not sufficient to optimise the entire manufacturing process which consists of sequential manufacturing steps. Instead, new comprehensive approaches towards dimensioning multi-level processes under consideration of technological interfaces and taking multiple criteria into account are required to achieve global optima. In this paper, a methodology for dimensioning multi-level processes is introduced. One of the main benefits of the proposed approach is that the contrary manufacturing targets which generally are classified according to quality, economy and ecology, are considered. The resulting overall target function consists of preference multipliers and standardised sub-criteria functions. High values of the target function point out combinations of process parameters that yield to multi-criteria optimised processes. Multilevel processes are depicted in parallel target trees which are combined in one assessment value. This approach was implemented in manageable software. The software, programmed in JAVA, HTML and SQL, contains the implementation of the algorithm. The user is able to implement individual processes, targets and criteria. This allows a software-based, holistic dimensioning of manufacturing processes regarding individual preferences.

Keywords: Multilevel Processes, Process Dimensioning, Multi-criteria Optimisation.

Presenting Author's biography

Aleksander Rabinovitch. After studying industrial engineering and management with focus on production engineering and controlling, Aleksander Rabinovitch works as scientific assistant at Leibniz Universität Hannover at the Institute of Production Engineering and Machine Tools. His research within the German Collaborative Research Centre 489 (SFB489), „Process chain for the production of high performance components based on precision forging technology", is focused on the development of new methods for holistic optimisation and dimensioning of processes as well as entire manufacturing process chains.

1 Introduction

In order to provide high quality products as efficiently as possible, companies are forced to optimise their manufacturing processes. An increase in productivity and cost-effectiveness combined with a high quality output requires a comprehensive optimisation approach considering different manufacturing targets. Generally, it can be distinguished between target values of machining processes referring to quality relevant, economic and ecological targets. The challenge is to optimise machining operations in dependence of these partial competitive targets. Furthermore, an optimisation needs to consider the multilevel characteristic of processes, as processes consist of multiple consecutive machining operations, e.g. roughing and finishing, which are connected by input and output parameters.

Various approaches for multi-criteria optimisation of manufacturing processes exist in literature and practice [1,2,3]. These approaches mostly do not allow a comprehensive consideration of the multilevel characteristic of manufacturing processes. Instead, they have been designed for specific processes. A fact which complicates an application in a different manufacturing environment tremendously.

In this paper, a software-based approach for dimensioning multilevel processes regarding contrary target values is introduced. Dimensioning in this case implicates a multi-criteria optimisation and the according determination of process values for each process level. A system architecture is provided, which allows a universal application and facilitates the modelling and dimensioning of processes with different characteristics. Firstly, a general overview about modelling and multi-criteria optimisation methods is presented. Secondly, a definition of process models and technological interfaces is introduced. Thereon, an approach based on a target tree method and its implementation in a manageable software environment is described. The presented approach is validated by dimensioning a gear grinding process.

2 Modelling and optimisation of manufacturing processes

A general procedure for dimensioning manufacturing processes is divided into the following steps: identification of input values, process parameters and output values, process modelling, and optimisation. For each step a various number of concepts is available.

2.1 Approaches for process modelling

The main tasks and functions of models are description, explanation of structures, functionalities and characteristics, prediction and decision-making for dimensioning of systems [4]. Dombrowski proposed guidelines for a structured procedure of system modelling [5]. Depending on the hierarchy and complexity of the system, a bottom-up or a top-down approach is adequate. Thereby, ElMaraghy points out, that the real or perceived complexity of processes and systems is related to the information which has to be processed. It increases due to the variety and the uncertainty caused by the variety or a lack of information [6]. Thus, depending on the system reality, each approach exhibits individual advantages.

In order to model information systems and data structures, Chen has developed the Entity/Relationship method [7,8]. These models consist of entities, attributes and relationships. It has been remarked, that these models lack of clarity if applied to complex interdependencies [9].

The same problem when dealing with model complexity occurs if artificial neuronal networks are used [10]. The artificial neuronal network is built up using the so called neurons. Input and output of the neurons are connected by the transfer function. The transfer function must not be described in detail as it is determined in an iterative debugging process. Artificial neuronal networks are often used for modelling and optimisation of manufacturing chains. In an early stage of modelling and optimisation, when knowledge is rare, neuronal networks are not appropriate for visualisation and structuring. Therefore, applying neuronal networks leads to higher benefits at a later stage of dimensioning, especially in the process of optimisation [9]. Monostori introduces an approach for generating multipurpose models of machining operations by means of artificial neuronal networks [1].

Fuzzy systems have similarities with neuronal networks [9,10]. Often, both complement each other in modelling and optimisation of manufacturing processes. The theory of the fuzzy logic extends the term of affiliation. This concept of fuzzy sets deviates from the Boolean modelling of elements and their attributes. For each element the degree of belonging to a fuzzy described subset is expressed by a real number between zero and one. The advantage of the application of fuzzy logic lies in the possibility to describe the behaviour of complex systems incompletely [11]. The application of fuzzy logic to model manufacturing processes is shown by the example of external grinding in [10].

An appropriate modelling approach for planning, analysing and dimensioning systems is the Structured Analysis and Design Technique (SADT). This method derives from the field of software engineering and depicts systems in convenient structures [12, 13]. The main focus of modelling with SADT consists of decomposition and modularisation. The application of SADT starts on the highest level of abstraction (overall system). The entire system is decomposed into single modules. The resulting subsystems again are decomposed in further modules. The subsystems of one level can be refined independently and connected by input and output parameters [12,13]. Examples for modelling manufacturing processes and entire process chains with SADT diagrams are shown in [9] and [14]. The reference process, continuous gear grinding, has been modelled using SADT diagrams.

2.2 Methods for optimisation

The optimisation step is based on the knowledge of parameters and interdependencies gained in the modelling stage. Existing optimisation methods can be divided regarding different criteria. In [15], a classification according to the two criteria: accuracy of the result of the optimisation and procedure of the applied algorithm is suggested. Referring to the criteria of the accuracy of the result, exact and heuristic approaches can be distinguished. Exact methods deliver accurate solutions which usually lead to tremendous computation time whereas heuristic approaches have been developed to calculate a nearest best solution with reduced computation effort. For this kind of approaches, the convergence and solution quality strongly depends on initial parameters which are often not exactly known [15]. A consideration of the procedure of the applied algorithm of the optimisation method leads to a distinction between deterministic and stochastic methods. While deterministic methods, e.g. the simplex-algorithm, follow implemented rules and require comprehensive knowledge about the solution space and target functions, stochastic methods instead include random values. Target functions, solution space and constraints are usually only known to a minor degree [15,16]. The best known stochastic method is the Genetic Algorithm (GA). This algorithm is used for optimisation of a single grinding process in [2] as well as for optimisation of consecutive process steps in the electronic production in [3].

Generally, problems in manufacturing are characterised by a set of criterions. This requires the application of multi-criteria optimisation methods. Compared to the commonly used optimisation techniques in the case of merely one criterion, these methods are characterised by a high degree of algorithmic complexity. Furthermore, the optimisation of multi-criteria problems often leads to multiple solutions. These results in a Pareto set of applicable alternatives. From this set, an optimal solution is chosen depending on the preferences of the decision-maker. Based on the moment, when the preferences are involved in the optimisation process, methods for solving multi-criteria problems are classified [17]. The classification includes non-preference methods, a-priori methods, a-posteriori methods and interactive methods. Within non-preference methods, solutions are obtained by relative simple algorithms and are accepted or rejected by the decision-maker. In interactive methods, the decision maker is fully integrated in the optimisation process. This leads to a high effort for the decision maker as he interacts from the start and has to select solutions at the very early stage. The most commonly used multi-criteria optimisation procedure are the a-priori and a-posteriori methods as depicted in Fig. 1 referring to [18].

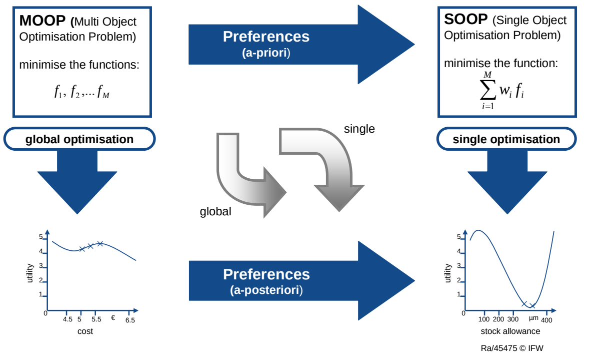

Fig. 1 Multi-criteria optimisation approach

Using the a-priori oriented method, the decision maker sets up his preferences as mathematical functions before the optimisation. Advantages of this approach are the restriction of the solution space before the computational based optimisation. However, in an a-posteriori method, firstly, a non restricted solution space is presented from which the decision maker chooses an alternative referring to his preferences. The advantage is a more comprehensive solution space available with sometimes new and innovative solutions which do not appear using the a-priori method [17]. Denkena et al. introduce a methodology which is based on the MOOP approach for dimensioning manufacturing process chains regarding multiple criteria. For validation, a process chain with precision forging technology for manufacturing gear wheels is chosen [14].

The preferences for choosing an optimal solution are fundamental for selecting a global optimum. For this reason, methods from the decision theory are used for determination of preferences and their application for choosing an optimal alternative. A method from the field of the decision theory is PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations). It is applied to conduct pairwise comparison of the acceptable alternatives within the solution space. Thereby, alternatives are ranked referring to their characteristic measured by multiple criteria [19]. Geldermann uses PROMETHEE for optimisation of the material and energy flow management in industrial lacquering process [19]. Another method for selection of alternatives in the field of decision theory is the Analytic Hierarchy Process (AHP). It structures the decision process into simplified levels. These correspond to the target, criteria, sub-criteria and the space of alternatives [11,19]. The decision maker investigates and determines relations of sub-problems of the decision. This procedure facilitates the decision making process tremendously. In [20], the AHP is used for estimation of production alternatives during the product planning.

After having introduced some techniques for process modelling as well as for optimisation and decision making, the next part of this paper addresses the software-based approach for dimensioning multi-level processes regarding contrary criteria.

3 Introduction of a software-based approach

First of all it should be mentioned that the provided methodology aims at a global optimised dimensioning of processes regarding multiple criteria, different constraints, as well as technological transfer parameters. The optimisation is conducted by means of the target tree method. Continuous grinding process of gearwheels is chosen as reference for validation.

Generally, a manufacturing process consists of sequential process steps, e.g. roughing and finishing. The result of the process step n is simultaneously the input parameter of process step n+1 [21]. The entirety of the transfer parameters between two process steps is defined as the technological interface, as shown in Fig. 2. Examples for technological transfer parameters are work piece conditions as e.g. macro geometry, stock allowance or temperature. These different conditions are shown in Fig. 2 as transfer parameters A, A' and A'' respectively.

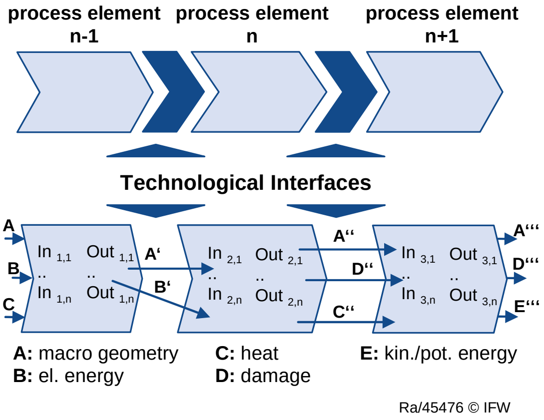

Fig. 2 Conception of Technological Interfaces

The consideration of technological interfaces between the individual process elements is necessary to achieve a global optimisation of the process. By modelling the interfaces, interdependencies between the process elements can be captured by the transfer parameters. These interface values are also regarded as input parameters for the optimisation. Without the consideration of interfaces, it is impossible to achieve global optima in manufacturing processes as important interdependencies are not taken into account.

Bearing this in mind, researchers at the Institute of Production Engineering and Machine Tools in Hannover have currently developed an approach for the optimisation of manufacturing process chains based on dimensioning technological interfaces [14]. This approach is not only applicable on process chains but also on single and multi-level processes. Depending on the considered object, the different levels of approaches for process dimensioning are qualitatively classified as illustrated in Fig. 3. Apparently, the complexity of the dimensioning is higher with the increasing number of parameters and interdependencies considered.

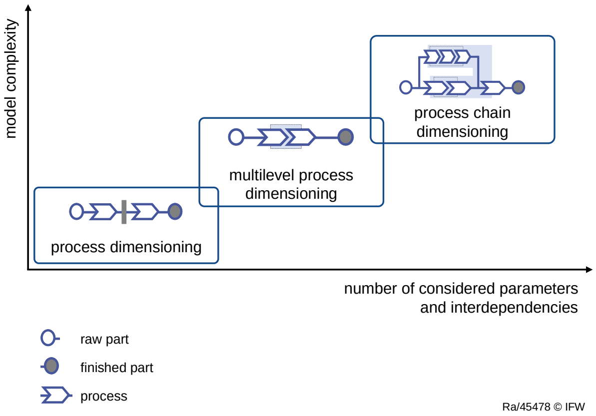

Fig. 3 Levels of process dimensioning

According to the developed complex method for the optimisation of manufacturing process chains, a new approach for the dimensioning of multi-level processes has been developed and implemented in manageable software.

3.1 Target tree method

The target tree method can be allocated to the group of value benefit analysis. Referring to the mentioned classification of multi-criteria optimisation methods, it belongs to the category of deterministic approaches. The method has firstly been implemented by Zangemeister in 1970 [22]. It is based on weighted coefficients which are used to balance different criteria corresponding to the preferences of the decision maker. These coefficients which are in the following called priorities reflect the preference for each criteria and sub-criteria. These priorities are identified by pairwise comparison. Fig. 4 exemplary shows a simplified target tree with three main criteria which are quality, economy and ecology. These are subdivided into further criteria. At each level of consideration, the sum of priority factors adds up to 1 [10,22].

In order to optimise a process, the criteria are combined in a single target function. This function contains normalised target values and priority factors. The resulting value of the target function is Z, the so called dimensioning value, as shown in Eq. (1) [21].

$$Z = \sum_{i=1}^{n} \left(1 - p_{xi} \cdot \left|\overline{x_i}\right|\right) \qquad (1)$$

Z value of the target function [-]

p_{xi}	priority factor [-]
x_i	target values of sub-criteria [var.]

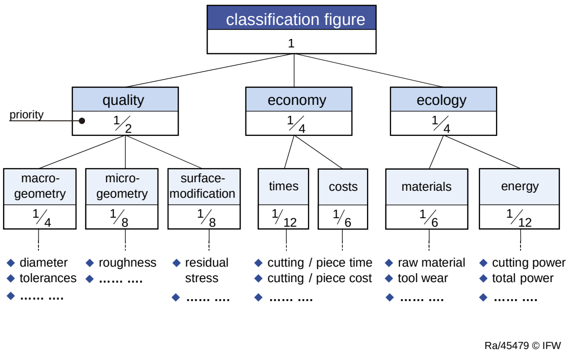

Fig. 4 Target tree containing three main criteria

As most of the target values of the criteria (x_i) require minimisation, e.g. times and costs, the criteria are subtracted from one. Due to this procedure, the value of the target function does no longer depend on the sign of the criteria. The aim is the maximisation of the value of the target function Z, whereas single criteria are multiplied with their corresponding priority. The higher Z, the more the criteria are satisfied according to the implemented preferences of the decision maker.

A consolidation of all criteria into one single target function requires that the criteria are normalised as they all have different units. Furthermore, absolute target values are used in the normalisation to exclude their different signs. The interval for the value range is chosen to be between 0.1 and 0.9. This interval is chosen for reasons of plausibility. It is expected that the overall dimensioning value Z never reaches the optimum of 1 and never decreases to 0. The procedure of normalisation is conducted for each criterion and is illustrated by the example shown in Fig. 5 [21].

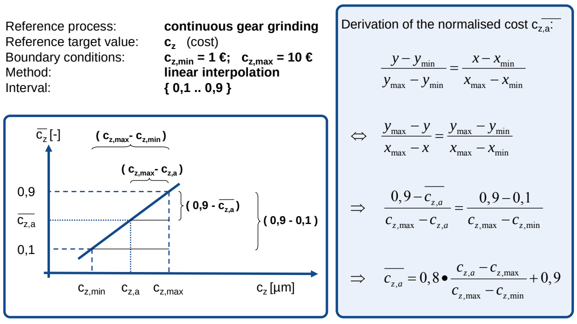

Fig. 5 Normalisation of a target value

After the normalisation, the criteria are all within a range of 0.1 to 0.9.

In the so accumulated target function, technological models for description of target values are implemented. Multiple levels of processes are depicted as particular target trees which are connected by technological interfaces, thus leading to a multi-level optimisation.

3.2 Implementation in a software environment

The presented target tree optimisation approach was implemented in manageable software. The aim was to implement the described optimisation procedure into a user friendly and independently applicable environment. That way, it will be possible to conduct an on-site application of the tool using a laptop connected to a server. The software contains the different functions to fulfil a dimensioning of manufacturing processes. Firstly, the mathematical models underlying the considered complex manufacturing processes can be registered and depicted. These equations are the fundament for the dimensioning procedure. Furthermore, the software offers the possibility, to define and visualise individual target trees for each process (as described in chapter 3.1). A 2-D and 3-D visualisation of the simulated data based on the mathematical models is available. Finally, the peaks in the simulated data can be identified which represent the maximal values for the overall target function Z. This allows the user to visually identify the optimal solution.

A server-client architecture has been identified as the most suitable approach. These two main components are a server which contains the required databases and the client to run the program as depicted in Fig. 6.

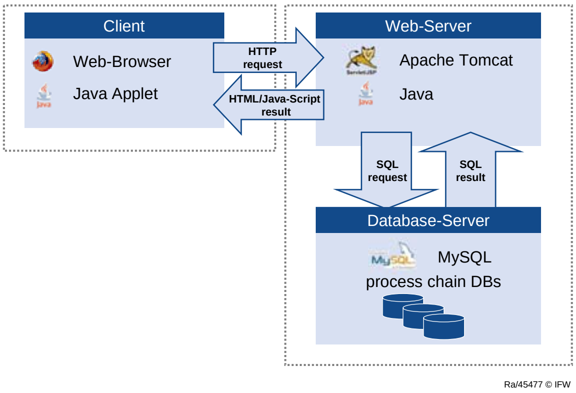

Fig. 6 Software architecture

The complete functionality of the client is implemented in HTML. The server-address leads to the startpage within a standard internet browser. This approach offers a widely usage of the software at different locations at the same time. The web-server uses Apache-Tomcat 6.0 as an interface between the client and the running optimisation-software. The requests of the client are delivered to the web-server which returns the results in HTML-format. The servlets are started by the web-server in the so called servlet-container and executed. Within the servlets, the communication (read and writing of datasets) takes place. The result pages are generated through java-servlets. Each process chain is saved in a separate data base. These databases contain information about the involved processes (mathematical models and categorisation, process variables, constants and target trees). Furthermore, a system database has been implemented which contains specifications about the mode of operation of the software.

3.3 Exemplarily implementation for a continuous grinding process

For validation of the approach as well as for the implemented software a continuous grinding process for manufacturing gear wheels is chosen (Fig. 7).

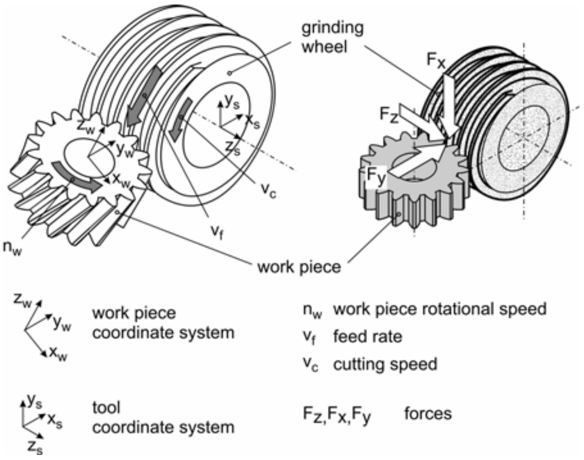

Fig. 7 Continuous grinding process

The continuous grinding process is characterised by input, process and output parameters. The parameters of this process have to be structured systematically. For this reason, the already mentioned SADT-diagrams are used. The parameters are divided in work piece, tool and process data. The gear grinding process is separated into two sequential steps: roughing and finishing. This way the characteristic of multilevel processes is taken into account. Qualitative illustration of this process including the technological interfaces is depicted in Fig. 8.

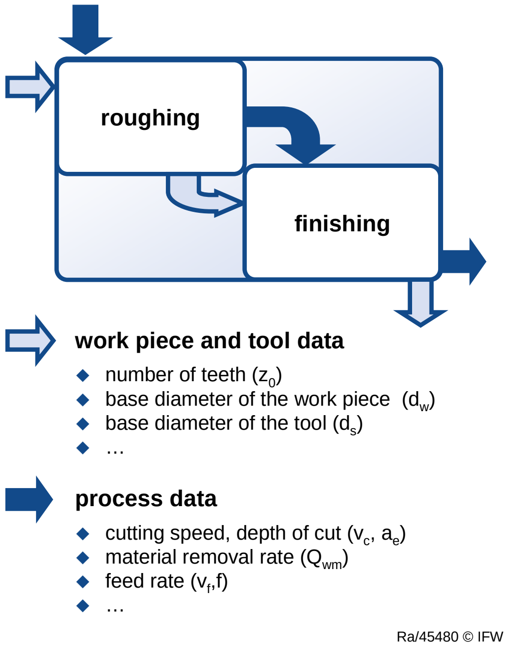

Fig. 8 SADT-diagram of a continuous grinding process

The equations and parameters presented in the following have been selected to illustrate the dimensioning procedure. Since the reason for this research is a first evaluation of the developed method in a software environment, a reduction of complexity is taken into account. The parameters of major importance for this manufacturing process considered in the dimensioning procedure are: feed rate, cutting speed and the technological transfer variable stock allowance. Further parameters and targets are possible [23,24].

In addition to the determination of the process parameters, the target values have to be defined. These are divided in three categories: economic, quality relevant and ecologic targets. By the example of the economic target values manufacturing cost per piece (Eq. (2)) and time for machining one piece (Eq. (4)), the implementation of formularised coherences in the mathematic model of the software is shown.

$$c = \frac{c_p}{L} + \frac{c_r}{L} + c_m + c_f \qquad (2)$$

c	cost per piece [€]
c_p	preparation cost [€]
c_r	repetition cost [€]
c_m	manufacturing cost [€]
c_f	following cost [€]
L	lot size [-]

Cost for manufacturing one piece consists of preparation cost, repetition cost, following cost and manufacturing cost which are based on machine hourly rate, as shown in Eq. (3).

$$c_m = t * \left(c_{mh} + c_s + c_w\right) \qquad (3)$$

c_m	manufacturing cost [€]
c	machine hourly rate [€]
c_w	tool wear cost [€]
c_s	salary hourly rate [€]
t	time for machining one piece [h]

The variable time for machining one piece can be referred to the feed rate as follows, Eq. (4). [23,24]:

$$t = \frac{n * H}{v_f * 60} \qquad (4)$$

t	time for machining one piece [h]
n	number of passes [-]
H	pass stroke [mm]
v_f	feed rate [mm/min]

Accordingly, quality relevant and ecologic target values are ascribed to the influencing variables cutting speed, feed rate and the technological interface variable stock allowance (a_e). The considered quality relevant targets are roughness depth (r_d) and feed rate marks (f_f). The ecologic target value is the energy consumption (e) as the result of the forces and the velocities in the process.

The obtained target functions are finalised in the overall target function. For roughing and machining, two different target trees are implemented. The underlying mathematical models are equal for these two processes, but are different referring to the implemented cutting speed and feed rate. Furthermore the technological interface variable stock allowance has to be adjusted.

The resulting overall target function which contains all considered parameters and is weighted based on the individual preferences (p_1 to p_5). It is shown in Eq. (5).

$$\begin{aligned} Z = {} & 1 - p_1 \cdot \left|\overline{c}\right| + 1 - p_2 \cdot \left|\overline{t}\right| + 1 - p_3 \cdot \left|\overline{r_d}\right| \\ & + 1 - p_4 \cdot \left|\overline{f_f}\right| + 1 - p_5 \cdot \left|\overline{e}\right| \end{aligned} \qquad (5)$$

The dimensioning of the grinding process is depicted in following figures, visualised in the developed software.

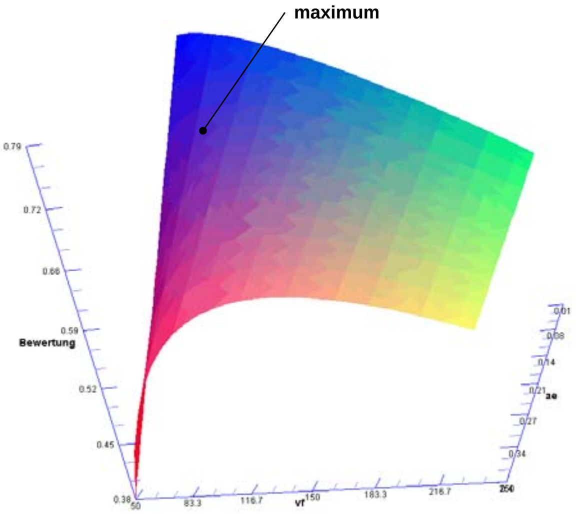

Fig. 9 Visualisation of the target function of the roughing process level

Fig. 9 shows the visualisation of the assessment value of the target function depending on the two parameters feed rate v_f and removal allowance a_e in the roughing process level. In the next figure, the assessment value is visualised based on the process parameters cutting speed v_c and feed rate v_f in the machining process step.

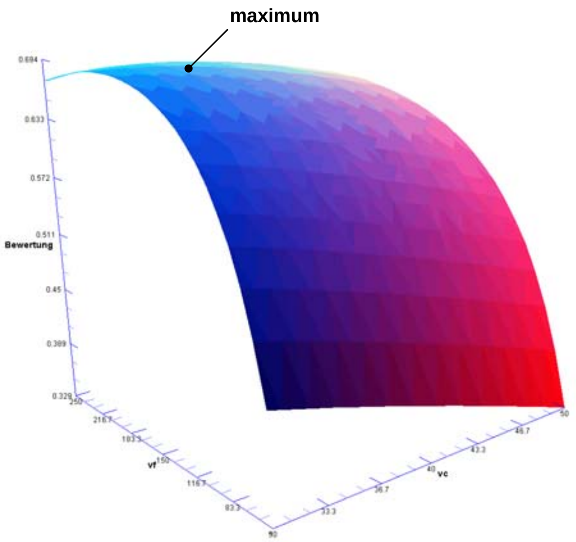

Fig. 10 Visualisation of the target function of the finishing process level

The optimisation is only shown for two process parameters to allow a 3D-visualisation, but the software automatically dimensions all process parameters for the corresponding global optimum. The optimal parameters are displayed in the software window besides the visualisation. This way, the developed approach allows the exploitation of potentials in multi-level manufacturing processes regarding multiple criteria.

4 Summary and outlook

The proposed method focuses on the dimensioning of multi-level manufacturing processes. Different and contrary target values are taken into account. The approach is based on the target-tree method which is implemented in a manageable software environment. The software is built in a server-client architecture with a process database. This offers the user an opportunity to model processes in a simplified manner and to determine the optimal settings for input and process parameters as well as technological interfaces. The dimensioning of the process is based on an overall target function which combines sub-criteria weighted with the decision maker's preferences. Further development in this area is the implementation of the Analytic Hierarchy Process (AHP) for the preference-based determination of the weighting factors.

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