Simulation-based dimensioning of manufacturing process chains

B. Denkena, J. Henjes, H. Henning*

Leibniz Universität Hannover, Institute of Production Engineering and Machine Tools, An der Universität 2, Garchen, 30823, Germany

© 2011 CIRP.

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Process planning
Simulation
Process chain optimisation
Discriminant analysis

ABSTRACT

Manufacturing process chains represent a sequence of specifically arranged, single processes to assure the production of a part. In the past, the focus lied on the optimisation of the individual processes in terms of lead or setup times and efficiency. These approaches disregarded the benefits which can be gained from the consideration of the existing interactions between the processes. Yet, it is very unlikely to achieve the holistic optimum of a process chain using this approach. Instead, a perspective shift is required which on the one hand leads to a higher system complexity to be handled but on the other hand leads to more promising results and harmonised processes. By implementing the definition of technological interfaces between the processes, a link between the processes is established and the effect of each parameter change on the performance of the subsequent processes can be modelled and assessed. In doing so, a general optimisation of the entire process chain can be obtained. In the presented paper, a simulation-based approach for modelling and dimensioning process parameters in a process chain as well as the corresponding technological interfaces is introduced to the reader. First statements about the optimal parameter settings for a holistic optimum of the process chain are derived by setting up a simulation of a reference process chain for pinion shaft production based on precision forging technology. In a second step, a discriminant analysis is applied as an alternative optimisation approach and evaluated for the presented production of pinion shafts.

1. Introduction

For each customer requirement, companies are setting up the adequate process chain in terms of sequence, timing, in-house production and feasibility. The process chains for manufacturing complex components from the automotive industry like for example gear wheels, pinion shafts or crankshafts contain several successive processes which need to be harmonised referring to the target system of the production planning of the company. Generally, the target system for machining systems as the backbone of manufacturing process chains commonly consists of quality requirements, cycle times and production costs. Nowadays, the consideration of ecological values has extended this traditional target system resulting in a system which consists of complementary and conflicting targets. For each target, a different solution for the optimal harmonisation of the process chain can be found. The basic assumption is that a holistically optimised process chain will be more efficient compared to individual optimised processes, as the consideration of technological interdependencies between the processes will lead to a better operation of the overall chain. Negative effects due to a single-process optimisation of a pre-located process on a subsequent process can be avoided. Thus, it is necessary to extend the perspective to a more comprehensive view in order to avoid an optimisation of individual processes within the production without considering the achievement of a holistic optimum of the process chain. Furthermore, it has to be considered that the final optimum strongly depends on the preferences of the decision maker and the weighting of the targets, thus on the individual culture and goals of the company.

The optimisation of successive machining operations in dependence of the described partial competitive targets takes place in the stage of production planning. Within this area, it is usually distinguished between process planning and process control referring to EVERSHEIM [1]. These areas include all tasks necessary for an adequate planning and processing of orders. The area of process planning for process chains consists of two main sub areas: process chain configuration and process chain optimisation [2]. The work presented in this article can be assigned to the field of process chain optimisation, as process chain configuration would deal with the substitution and arrangement of alternative processes which is not part of this study. An overview can be found in Tönshoff et al. [3].

In the following, an investigation of the advantage of a holistic compared to a single-process oriented optimisation of process chains is introduced. In order to extend the dimensioning...
procedure to a holistic point of view, the term of technological interfaces is introduced and applied. At first, an overview about the state of the art in process optimisation is given to the reader. Then, the reference process chain is introduced in terms of process chain analysis and modelling. The chapter contains the conceptual formulation of the developed method for a comprehensive process chain optimisation. The next section describes the implementation of the developed models for each process in the discrete simulation software environment. The chapter is followed by the description of the results gained by both a local and a holistic optimisation. Finally, a description of a method for fast computation of holistic optimal process parameters is given.

2. Dimensioning of process chains

2.1. Single-process oriented dimensioning

The optimisation of process chains based on an individual optimisation of each process involved without considering interdependencies to subsequent processes is referred to in this paper as single-process oriented dimensioning. This definition will be used throughout the article. Generally, this concept will lead to an optimal parameter setting for each machine being involved in the manufacturing process chain. Several advantages can be identified: First of all, the concept is very clear and understandable for the experts on the shop floor level. From the mathematical point of view, each process represents an individual optimisation problem which has to be solved by an adequate optimisation technique. Optimisation techniques can be exact or heuristic which are described in detail for example in [4]. A description of the application of optimisation algorithms to manufacturing processes can be found in [5]. It has long been state of the art in manufacturing optimisation to focus on the dimensioning of single processes within the material flow [2]. The observed reservation in the application of holistic approaches in process chain optimisation can be attributed to the fact that the real or perceived complexity of processes and systems is related to the information which has to be processed [6].

As each decision about an optimal parameter setting determines not only economic or ecological values, but does strongly influence the technological characteristics of the product, it is questionable whether the achieved optimum based on this approach does indeed represent the overall optimum of the process chain. For example, the stock allowance, which is the output value of the precision forging process and at the same time the input for the final grinding process should be introduced as an example. From the perspective of the forging process, it would be reasonable to achieve a wider stock allowance in order to reduce the costs of the cavity. From the point of view of the grinding process, the stock allowance should be as small as possible in order to achieve a minimal production time. Such a trade-off can neither be modelled nor be measured by these traditional approaches for process chain dimensioning. Therefore, in the next section, an overview about existing approaches for holistic process chain optimisation which overcome these limitations is given.

2.2. Holistic process chain dimensioning

The consideration of both processes as well as the interactions in a comprehensive approach is referred to as holistic process chain dimensioning. This term is defined in this article to illustrate the difference to the previous concept of local single-process oriented process chain dimensioning. An increasing amount of papers dealing with this area of research could be observed in the recent years. Eichgrünn points out that a comprehensive identification of causes and effects requires a consideration of process chains as a whole [7]. He describes an approach based on six sequential steps to increase process reliability of manufacturing process chains by means of holistic analysis, design and control. Reinhart presents a generic target system that describes the requirements on subprocesses and the entire value added chain, respectively [8]. Based on the implemented electronic trading platform, so called demand vectors are generated for certain tasks in the process chain. Regarding competence profiles of process chain elements, compliance vectors for these tasks are introduced. A reference model for the analysis and configuration of production process chains is developed by Schäfer [9]. He focuses on the application of techniques for the analysis of causes and effects in process chains as a complete system. Warnecke describes an integrated approach for process chain design within manufacturing environments for ceramic products as the key to an economy oriented and highly efficient process chain [10]. A holistic view on a process chain is regarded to be of special importance. These approaches have in common that the focus is on the consideration of the process chain as a whole, not on separate processes. An overview on multi-criteria based optimisation techniques for the optimisation can be found in [11].

3. Conceptual formulation

3.1. Definition of technological interfaces

The term of technological interfaces has first been defined by Tönshoff et al. [12] and was applied to a process chain for gearwheel manufacturing based on the DTI-Method. The DTI-Method stands for “Designing Technical Interfaces” and consists of four consecutive phases: process analysis, interface modelling, optimisation and implementation. The method is partially applied in the presented paper. A chain of processes can be identified in several different levels in the shop floor. From a more general point of view, the optimisation of the process chain is considered. The single processes of this process chain again consist of several sequential steps which can be defined as the step of multilevel or multipass process optimisation.

Fig. 1 illustrates the different levels for process chain dimensioning. For the level of process chain optimisation and multilevel process optimisation, the concept of technological interfaces can be applied. For example, in the area of multilevel process optimisation, the optimisation of a crankshaft grinding process can be considered. Consistent to the presented approach in this paper, the individual parameter settings in each process step like grinding wheel velocity, crankshaft velocity and the material removal rate have to be optimised for roughing, finishing and spark-out which are connected by the technological interfaces like for example the stock allowance for the finishing operation. A first outlook over this concept is given in Denkena et al. [13].

![Fig. 1. Levels of process dimensioning.](image-url)
assumption of considering technological interfaces can be transferred to a process chain dimensioning and is shown in Fig. 2.

Fig. 2 illustrates the term of technological interfaces which represent the number of transition values between the individual processes. The dimensioning is based on models which need to be gained from the processes. These are derived in the phase of process analysis and modelling. A process chain consists of individual process elements which are affiliated with each other along a timeline. A process element is understood as an arranged succession of activities which transfers a defined input into a defined output [13]. In common manufacturing processes, the input consists of several parameters which in an interaction create multiple output values. Within the process chain, the output of a process element represents the input of its successor. The transition between two process elements can be considered as a technological interface, including all parameters which significantly influence the successive manufacturing steps. Thus, the output of one manufacturing step (n) is simultaneously considered to be the input for the following step (n + 1). There is a transition state as the preceding process influences boundary conditions or the process performance of succeeding processes in the process chain. Thus, the concept of technological interfaces is well in line with the shown approaches in the area of holistic process chain optimisation.

The consideration of technological interfaces has therefore been chosen as the most adequate approach and has been implemented in the simulation for the comparison to the single-process oriented process chain optimisation. The dynamic process models and the technological interfaces are both implemented into a simulation for a reference process chain for pinion shaft production. The application of the shown concept requires a comprehensive process chain analysis and modelling at an earlier stage. These are described in the next chapter.

3.2. Process chain analysis and modelling in the reference process chain

A comprehensive analysis of all processes involved in the manufacturing of complex components like the presented pinion shafts requires a high degree of expertise. This knowledge is usually restricted to a certain amount of experts within the company involved in the manufacturing process. In cooperation with these experts, the processes and technological interfaces within the considered process chain have to be distinguished and analysed. Therefore, the individual processes have to be abstract and carefully simplified, leaving just the significant information. As a prerequisite for the later phase of process modelling, first assumptions about the targets have to be created in order to determine the systems to be modelled. The result of the process chain analysis is a detailed description for later process models and the interdependencies between processes which define technological interfaces. For the reference process chain of pinion shaft production, the following processes have been identified. Fig. 3 illustrates the workflow of processes for the pinion shaft manufacturing based on precision forging with integrated heat treatment.

The chosen reference process chain contains all process steps from the rough part till the finished part. Details of the reference finished pinion shaft are given in Table 1. Due to the given system complexity, a complete analysis of the process chain cannot be depicted as this would be too extensive for the purpose of this article. For each process, the corresponding process models have to be derived according to the defined target functions.

During the development of the process models, the interdependencies between the processes become apparent and are documented for the definition of the technological interfaces. In the next step, the data gained in the phase of analysis is used to create process models. The main task and function of models are description, explication of structures and functionalities of systems for the prognosis and decision making in the optimisation of systems [14–16]. In the reference process chain, the individual steps for manufacturing the pinion shaft like chipping or forging and the following steps of hardening and machining are considered as separate processes. As mentioned in Section 3.1, a process is defined as a transformation of input values of a system to corresponding output values. For forging, the input consists of values like for example geometry, surface, temperature, material, etc. During the transformation of the part, a force is induced on the part by the cavity and the form of the part changes accordingly. This in turn changes the characteristics of the part and leads to new

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction of edge</td>
<td></td>
<td>Right</td>
</tr>
<tr>
<td>Number of teeth</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Diameter of base circle</td>
<td>(mm)</td>
<td>59.4</td>
</tr>
<tr>
<td>Pressure angle</td>
<td>(°)</td>
<td>20</td>
</tr>
<tr>
<td>Helix angle</td>
<td>(°)</td>
<td>20</td>
</tr>
<tr>
<td>Total length</td>
<td>(mm)</td>
<td>120</td>
</tr>
<tr>
<td>Width of gear wheel</td>
<td>(mm)</td>
<td>20</td>
</tr>
<tr>
<td>Pitch circle diameter</td>
<td>(mm)</td>
<td>63.66</td>
</tr>
<tr>
<td>Root diameter</td>
<td>(mm)</td>
<td>58.66</td>
</tr>
<tr>
<td>Outside diameter</td>
<td>(mm)</td>
<td>67.7</td>
</tr>
<tr>
<td>Material lot 1</td>
<td></td>
<td>42CrMo4</td>
</tr>
<tr>
<td>Material lot 2</td>
<td></td>
<td>16MnCr5</td>
</tr>
</tbody>
</table>
output values for geometry, surface, temperature or hardness. The transformation requires a defined amount of time. The output values are referred to as transfer values and define the technological interface between the sequential processes. For example the volume of the rough part, which is determined at the process separation has to be in accordance with the required volume of material of the precision forging process. A shortfall would not fill the cavity completely and the part would be defective. In the contrary case, if the volume of the rough part would exceed the proposed forging volume, the cavity would not close completely which would lead to wear at the forging matrix. Another example is the temperature of the work piece, which represents the most significant factor in the processes of heating, precision forging and heat treatment. A cooling below the required temperature between the processes has to be avoided, as this would require the integration of another process for the anew heating. The described interdependencies and the effects on the target values are shown in Fig. 4, whereas $d_1$ represents the diameter of the semi-finished product, $V_{kh0s}$ is the volume of the blank, $\beta_1$ and $\beta_2$ are temperatures, respectively. The stock allowance is described by the parameter and the time for the stock allowance oriented precision positioning is referred to by $t_{AF}$.

Using the described concept based on process chain analysis and on process chain modelling the term of technological interfaces, a continuous identification of the most significant parameters throughout the process chain becomes feasible. After the process chain has been analysed and a model has been created, the data is transferred in the simulation software. The developed simulation is described in the next chapter.

4. Simulation of the process chain

In order to gain an overview about the different impacts of both the single-process oriented dimensioning and the holistic optimisation, a simulation has been set up. The simulation has been created in Plant Simulation®1, a discrete simulation environment. For more information on event-driven simulations refer to Sauerbier [17]. An overview about the developed simulation environment is given in Fig. 5 which only contains the modelled process chain for the pinion shaft manufacturing at the topmost level. The processes of decollating, precision forging and hard-finishing themselves are modelled as networks which is not shown in Fig. 5. In order to determine a first operational point for the process chain, a design of experiments has been setup with different parameter settings. Several parameters have been identified having a major influence on the targets of the manufacturing process chain. These parameters can be either transfer values or process parameters. A selection of parameters and the intervals for the simulation is given in Table 2. In the column “Type”, the parameters are distinguished referring to process (“P”) and transfer values (“T”).

The number of trials has been reduced using fractional design of experiments. For the single-process oriented optimisation, it is necessary to identify one major process as an initial point for the setting of transfer values like temperature or stock allowance. Depending on the target value, a process has been selected. For setting the temperature referring to cost and time, precision forging has been chosen whereas heating has been selected for the determination of the optimal value for the technological interface values referring to energy. For the stock allowance of the tooth flank, the precision forging has been selected for all targets, whereas for the stock allowance for the bearings the process of hard turning has been chosen.

The two lots within the regarded scenario are simulated consecutively to allocate the arising setup times and costs only to the corresponding lot of homogenous material. First, the lot of the pinion shaft made of 42CrMo4 has been simulated. The simulation leads to an enormous amount of data which have to be evaluated for the single-process oriented and holistic optimised process chains which are simulated separately. The results of the simulation are given in the next chapter.

4.1. Results from the simulation

Generally it can be shown that the implementation of transfer values in the technological interfaces strongly influences the parameter settings. There is a definite difference between the single-process oriented and holistic optimised process settings which can be observed. For example, referring to the heating temperature, a single-process oriented optimised process would...

---

**Table 2**

Ranges and types of parameters.

<table>
<thead>
<tr>
<th>Description of the parameter</th>
<th>Type</th>
<th>Unit</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decollating velocity</td>
<td>P</td>
<td>m/min</td>
<td>150</td>
<td>350</td>
</tr>
<tr>
<td>Decollating feed rate</td>
<td>P</td>
<td>mm</td>
<td>0.27</td>
<td>0.67</td>
</tr>
<tr>
<td>Heating temperature</td>
<td>T</td>
<td>°C</td>
<td>1000</td>
<td>1400</td>
</tr>
<tr>
<td>Stock tooth flank</td>
<td>T</td>
<td>µm</td>
<td>25</td>
<td>250</td>
</tr>
<tr>
<td>Stock bearing</td>
<td>T</td>
<td>µm</td>
<td>100</td>
<td>220</td>
</tr>
<tr>
<td>External cylindrical grinding infeed</td>
<td>P</td>
<td>mm</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>External cylindrical grind. work-piece velocity</td>
<td>P</td>
<td>m/s</td>
<td>0.15</td>
<td>0.35</td>
</tr>
<tr>
<td>External cylindrical longitudinal feed</td>
<td>P</td>
<td>mm/U</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Hard turning feed rate</td>
<td>P</td>
<td>mm</td>
<td>0.05</td>
<td>0.4</td>
</tr>
<tr>
<td>Hard turning cutting speed</td>
<td>P</td>
<td>m/min</td>
<td>140</td>
<td>220</td>
</tr>
<tr>
<td>Continuous grinding feed rate</td>
<td>P</td>
<td>mm</td>
<td>0.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Continuous grinding wheel velocity</td>
<td>P</td>
<td>1/min</td>
<td>3800</td>
<td>6500</td>
</tr>
</tbody>
</table>

---

lead to an optimal value of 1200 °C whereas in a holistic optimised process chain a value of 1000 °C would be preferable leading to a difference in the settings of 20%. Another difference can be observed in the settings for the stock allowance for the tooth flank which differs from 275 μm to 25 μm. This significant difference needs an explanation and is directly connected to the process planning. As shown in Fig. 4, the stock allowance is determined in the stage of precision forging. The stock allowance reflects a trade off referring to the total costs of the process chain. A high stock allowance decreases the requirements for precision of the cavity in the forging process and leads to increasing production costs in the grinding process of the tooth flank as a larger amount of material needs to be removed. Referring to the approach of using single-process oriented process optimisation, the stock allowance is determined based on the optimisation of the precision forging process. Due to the high costs of the cavity it is in this particularly case optimal to determine the stock allowance for the tooth flank at a high value, i.e. at 275 μm. This will reduce the wear of the cavity and increase the tool life without regard to increasing costs in the following process of continuous grinding. In case of a holistic optimisation of the process chain, the consideration now includes the costs of the continuous grinding process, thus the trade-off is considered in the dimensioning of the parameter setting. The internalisation of the trade-off leads to the determination of a different optimal transfer value of 25 μm. This example emphasizes the benefits of the holistic process chain optimisation. Trade-offs which before have been considered as external effects in single-process oriented process chain optimisation are now included in the process planning as parameters of the technological interfaces. The computation time for the holistic process chain optimisation exceeds that for a single-process oriented dimensioning tremendously. Thus, an approach has been investigated to solve this issue. The discriminant analysis is an adequate method and has been applied to this research as described in the following.

4.2. Applying discriminant analysis to holistic process chain dimensioning

To determine optimal parameter settings in a holistic optimised process chain during the manufacturing process because of manufacturing tolerances and disturbances it is not practicable to compute the optimal technological interfaces in a longer time than the process time. So, the bottleneck of a process chain is the optimisation method. Thus, an advanced approach based on the above described method was developed.

This approach deals with the application of correlation and discriminant analysis. Dependencies of variables are determined by the minimization of the distances to a correlation function in a correlation analysis while the influence of variables on a group assignment is examined by a discriminant analysis [18].

The aim is to identify technological interfaces which show a significant influence on target values (technological, economic, logistical and ecological). Furthermore, it is examined how these interfaces have to be dimensioned qualitatively and quantitatively for a holistic optimal process dimensioning. Therefore, the formation of a discriminate function is taken from the discriminant analysis. Thus, possible combinations of attribute expressions have to be evaluated.

To carry out a discriminant analysis, a sample of a statistical sufficient scale is required. Based on this sample, the influence of the attribute variables on classification attributes is examined. These classes distinguish the attribute combinations in the application on hand in fulfilling quantifying parameter. In the context of the process chain optimisation, three classes are defined using the aim attainment degrees.

For the generation of a sufficiently big sample an experiment layout composed of 33075 runs with the above described material flow simulation is generated with the help of the correlation analysis. In the following, data groups are classified, which is done by a separation referring to the simulated target values. The best 5% of the runs which reach the highest aim attainment degree are summarized in one group. The other two groups are defined analogously (Fig. 6). The choice of the groups was justified in finding excellent combinations of the attribute variables.

Finally, the discriminant function is determined. To this function, combinations of variables can be assigned under a certain safety to one group. From these results the influence of the individual variables on the connection to the group can be described. A final revertive check of the sample on the assignment to a group in the comparison with the known group assignment showed that 87.5% of all samples would have been assigned to the correct group by the discriminant function. It also has to be mentioned that a wrong assignment to a better group significantly appears to be more rarely than an assignment to a worse group. This confirms the meaningfulness of the discriminant function.

5. Summary and outlook

In this paper, the approach of dimensioning manufacturing process chains is investigated and compared to the conventional approach of single-process oriented optimisation. The developed method for holistic process chain optimisation is based on the additional consideration of technological interfaces which are included in the simulation. As it is shown, an optimisation of single processes leads to a different set of parameter values compared to the optimisation with the developed approach of holistic process optimisation. It can be stated that the holistic process chain optimisation offers a new and appropriate perspective for achieving highly efficient process chains. By applying a discriminant analysis, it is possible to determine optimal technological interfaces by less than seconds due to the simple discriminant function. So, in future it will become possible to transfer the described method in the process control.

Acknowledgments

The investigations described in this paper were undertaken with support of the German Research Foundation (DFG) within the Collaborative Research Centre “Process chain for the production of high performance components based on precision forging technology” (CRC 489).
References


Ursache-Wirkzusammenhänge und zur Ableitung von Maßnahmen zur Prozesssicherung, FBK produktionstechnische Berichte, Kaiserslautern.


