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PRODUCTION MANAGEMENT

Robust technology chain design: considering undesired interactions within the technology chain

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Abstract Existing methodologies in technology chain design are used to plan the deployment of manufacturing technologies under consideration of interactions between these technologies and workpiece properties. Present methodologies focus on workpiece characteristics which the technologies are designated to change. However, workpiece properties can also be negatively affected because of interactions between the manufacturing technologies and features which the technologies are not supposed to change. These undesired interactions can cause a lower quality of the produced parts and an increased amount of defective parts. In this paper, a new methodology is presented which enables the user to identify undesired interactions during the technology chain design process. Firstly, the product to be manufactured is analyzed and described as a set of individual features. Secondly, feature-specific technology chains are designed under consideration of possible undesired interactions. Thirdly, the individual feature-specific technology chains are merged to generate a robust technology chain for the manufacturing of the analyzed product. Since undesired interactions usually occur during production ramp-ups for the first time, the methodology is applied to a case study concerning a ramp-up in the automotive industry. In this context, improving the process stability by preventing the occurrence of undesired interactions is of high economic importance.

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1 Introduction

Technology chain design is an ongoing topic in the research area of production engineering [1]. Key reasons for employing technology planning methodologies in companies are the possibility of a systematic consideration of innovative technologies and the cost reduction by integrating technology planning in the product development process in order to maintain competitive advantages [2]. Comprehensive approaches in technology chain design can include multiple aspects such as the planning of manufacturing networks [3] or automated assembly process planning [4]. This paper focuses on technology chain design on the operative level and on interactions within individual technology chains. Earlier publications in the field of operative technology planning focus on the selection of suitable technologies to fulfill a manufacturing task [5]. A thorough analysis of interactions between technologies and workpiece characteristics is not included in these early approaches. Newer approaches consider interactions between the deployed technologies and interactions between the technologies and workpiece characteristics along the technology chain [6]. Undesired interactions between technologies and workpiece features are not considered in these scientific approaches. However, companies often struggle with problems from undesired and unexpected interactions within the technology chain. These problems lead to a high quantity of defect parts [7]. Therefore, the aim of the present paper is the development of a new methodology for robust technology chain design by considering undesired interactions along the technology chain.

2 Definition of key terms

Feature In this paper, features are defined as information sets which concern macro geometry, micro geometry, near surface zone characteristics, material properties and functions of a product's region of interest [8]. A feature represents a surface or volumetric element of a product, which fulfills one or several specific functions, e.g. a thread (feature) for the fixation of a screw (function).

Technology chain Referring to Klocke et al., a technology chain is an abstract combination of manufacturing technologies in a defined sequence with the purpose of manufacturing one, several or all features of a product and their characteristics [5].

Transition variables According to Klocke et al., transition variables describe properties stored in a feature due to mechanical, thermal and chemical effects of previous technologies. The transition variables describe the feature's characteristics at the interface between manufacturing technologies within a technology chain and have a specific value. Exemplary transition variables of features are surface roughness, form deviations or material hardness [9]. In this paper the term variable describes the transition variable of a feature, if not mentioned otherwise.

Function Referring to Heller and Feldhusen, the term function describes the general and desired correlation between the input and output of a system with the objective of fulfilling a task [10].

3 Methodology

This paper focuses on the design of technology chains under consideration of undesired interactions within the chain. It is assumed that the design process of the product to be manufactured is finished and that no further modifications of the product are required. Furthermore, it is assumed that the functions the product needs to fulfill are defined in a function list. An overview of the methodology is depicted in Fig. 1.

The methodology consists of two sections. In the first section (feature-oriented point of view), the product to be manufactured is subdivided into features and for each feature-specific requirements concerning its transition variables are defined (Sect. 3.1.1). Manufacturing technologies which are able to generate transition variables according to the requirements are systematically identified (Sect. 3.1.2). Furthermore, impacts these technologies can have on other features' transition variables are also identified (Sect. 3.1.3). All transition variables, a technology affects, are then depicted in technology modules (Sect. 3.1.4). Subsequently, the technologies are connected to feature-specific technology chains (Sect. 3.1.5).

In the second section (product-oriented point of view), the feature-specific technology chains are connected to design a technology chain for the manufacturing of the whole product. For this, constraints regarding the sequence in which features are to be manufactured (Sect. 3.2.1) as well as constraints regarding the sequence of manufacturing technologies are identified (Sect. 3.2.2). In the final step, feasible technology chains for the product manufacturing are designed (Sect. 3.2.3).

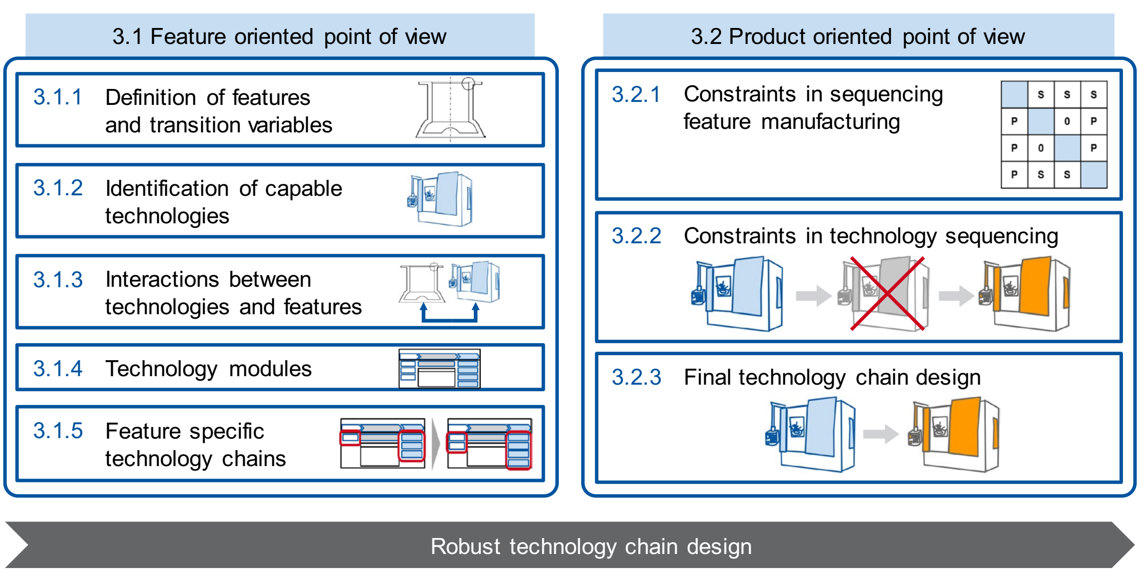

Fig. 1 Main steps of the methodology for robust technology chain design

3.1 Feature-oriented point of view

3.1.1 Definition of features and transition variables

In this paper, features are considered as function carriers (compare Sect. 2). Functions are divided into several levels of sub-functions. All sub-functions on one level must be fulfilled to enable the fulfillment of the (sub-) functions on the next higher level. These sub-functions are enabled by physical effects which depend on part characteristics that are regarded as transition variables with a corresponding parameter value [10].

To illustrate the significance of the determination of the transition variables' values, the example of a left ventricular assist device (LVAD) is considered. One of the functions an LVAD needs to fulfill is its blood compatibility. A sub-function of blood compatibility is mechanical blood compatibility which means that blood cells must not be damaged because of mechanical effects. Physical effects which negatively affect the sub-function mechanical blood compatibility are slashing and stockpiling of blood cells. Slashing occurs when the edge rounding of features which are in physical contact with blood is too low. Stockpiling depends on the amount and depths of undercuts on the features' surface. This example shows how the fulfillment of functions depends on the parameter values of transition variables.

Corresponding to the axiomatic design framework by Suh, the features of a product are identified by mapping functional requirements on physical product elements [11]. Based on this framework, a procedure to systematically identify features of technical products was developed (Fig. 2). In order to identify the features (F) of a product, functions and manufacturing requirements (Fn) are assigned to surface and volumetric elements (S) of the product (Fig. 2, left) [2]. Manufacturing requirements do not relate to the tasks a product needs to fulfill when used. Instead, manufacturing requirements describe the mandatory characteristics of a part to assure that subsequent manufacturing steps can be executed. Thus, a part cannot be manufactured if manufacturing requirements are not fulfilled. It is possible that one surface or volumetric element enables the fulfillment of several functions or manufacturing requirements. Likewise, it is possible that a function is fulfilled by several surface or volumetric elements.

In order to apply the presented methodology, requirements on the parameter values of transition variables need to be investigated. Figure 2 (right) schematically depicts the requirements concerning values of transition variables in a feature–function–matrix. Its purpose is to define the requirements for the values of transition variables so that the functions and manufacturing requirements of the features can be fulfilled. The value of a transition variable can be required to be higher or lower than a threshold value. Furthermore, it can have a direction for optimization where mathematically high (or low) values are preferred. Additionally, both conditions can be applied to a transition variable when its value is required to be higher (lower) than a threshold value and mathematically higher (lower) values are preferred [12]. Each column of the matrix contains the required values of transition variables in order to achieve a specific effect. This is either a defined range of values or all

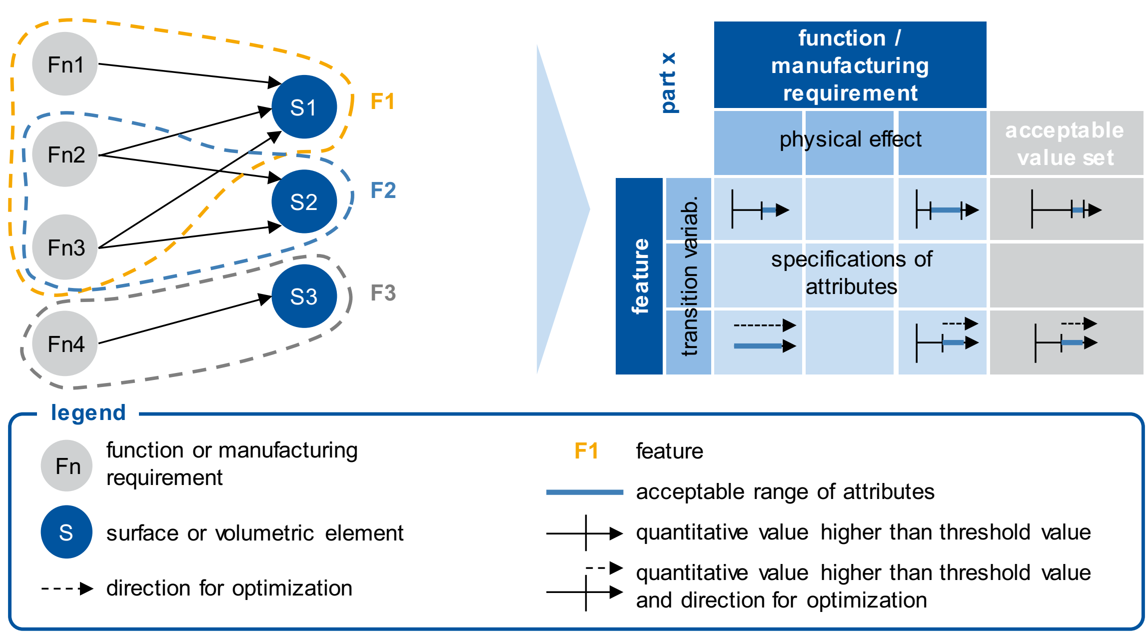

Fig. 2 Mapping of requirements to features in a feature–function–matrix

values higher or lower than the threshold value. The acceptable value set for each transition variable is the intersecting set of all requirements to values in one row of the matrix. If this set is empty, the requirements to the product's functions cannot be fulfilled. In this case, the methodology is not applicable until the product is redesigned.

3.1.2 Identification of capable technologies

In this step, technologies which are capable to manufacture a feature's set of acceptable values of transition variables are identified. DIN 8580 provides an overview and a systematic classification of manufacturing technologies. It can be used as a starting point for the manufacturing technology identification process (Fig. 3) [13].

At this stage of the methodology no specific machines are selected. Therefore, the capabilities of technologies need to be estimated with help of scientific literature and expert knowledge. Suitable technologies are identified by comparing the values of transition variables they are capable to generate to the set of acceptable values which was identified in the previous step.

A manufacturing technology is not required to change all transition variables of a feature. Features can also be manufactured by a combination of technologies. If a technology or a combination of technologies is capable of generating transition variables with values which belong to the set of acceptable values of a feature, these technologies are considered further in the following step. In the example in Fig. 3, the results of the technology identification step are three options for the manufacturing of the feature F1 (Fig. 3, bottom). It can be manufactured by combining technologies MT1 and MT2, by technology MT3 or by combining technologies MT2 and MT4.

3.1.3 Interactions between technologies and features

After capable manufacturing technologies have been identified, they are further investigated regarding the possible interactions with transition variables of features which are

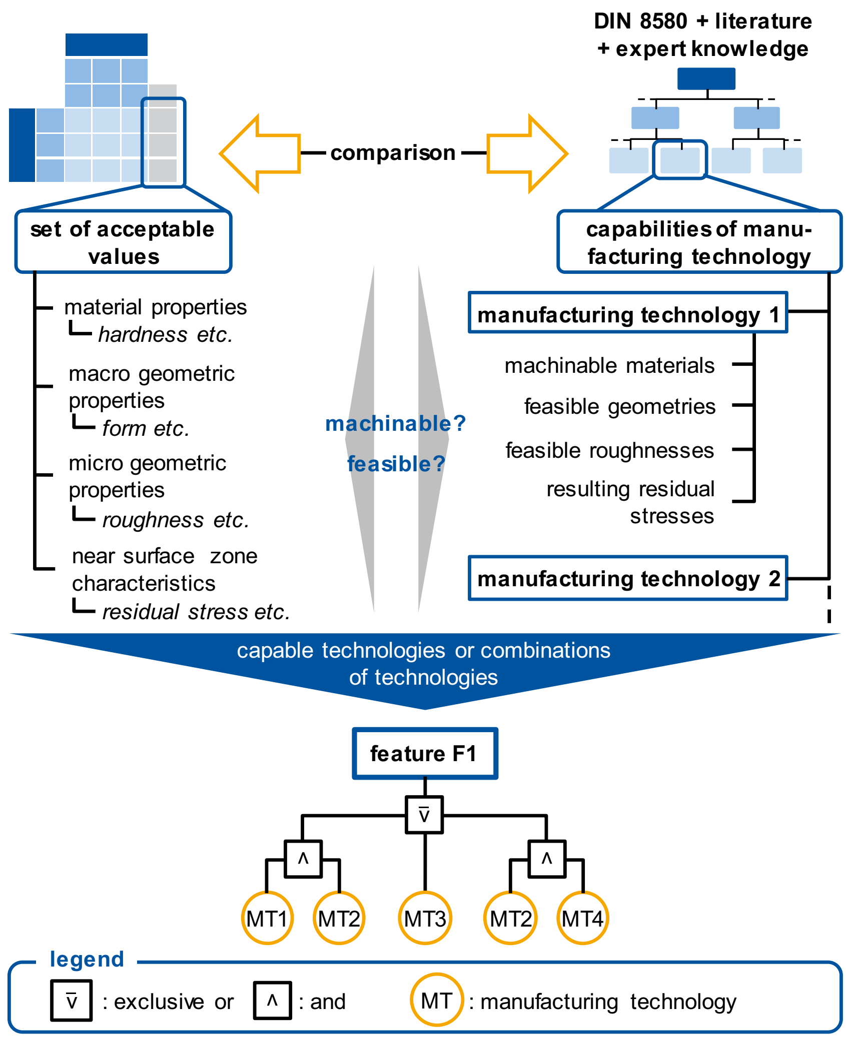

Fig. 3 Identification of capable manufacturing technologies

to be changed by the technologies. In contrast to previous publications in technology chain design, transition variables which are changed unintendedly because of undesired interactions in the technology chain are considered in this paper. For this, transition variables are categorized as primary variables and secondary variables. *Primary variables* are transition variables of a feature which are designated to be machined by a technology in a specific production step. Every technology machines at least one primary variable. Due to interactions during the deployment of manufacturing technologies, the machining of primary variables can cause unintended and potentially undesired changes of further transition variables of other features. Transition variables which are changed because of this kind of interaction are called *secondary variables*. Secondary variables can be affected by direct technology impacts as well as by side effects of a technology (Fig. 4).

When changed because of a direct technology impact, the technology effect on the secondary variable is similar to the technology effect on the primary variable. For example, if the surface of a feature is to be treated in an acid bath, but the protection of other product features from the acid is insufficient, then these features are influenced because of a direct technology impact (Fig. 4, left).

Side effects occur when the transition variables of a feature are changed and the cause of the change of the secondary variable differs from the cause of the change of the primary variable. During a milling operation transition variables can for example be affected by hot chips welded on features and by thermal conduction which leads to a workpiece distortion due to residual stresses stored in the workpiece [14]. As these causes of transition variable change are a result of the milling operation but are not essential for the machining of the primary feature (in this case the macro geometry), a change of secondary variables is caused by side effects (Fig. 4, right). The reasons for the occurrence of side effects are specific to each process and therefore need to be investigated individually. The resulting information of the process analysis is summarized in a table for each feature, compare Fig. 5 for feature F1.

A similar table is to be set up for every feature of a product. In the first column (“A”), technologies which were identified as capable to manufacture the considered feature are listed. The second column (“B”) contains the primary variables of each identified technology. The column “C” contains features which are influenced due to direct technology impacts and column “D” the effects on the corresponding secondary variables. The last two columns “E” and “F” contain information about the secondary variables of specific features, which are affected because of side effects. In the next step, the information in Fig. 5 is aggregated into technology modules.

3.1.4 Technology modules

Technology modules contain information about potential interactions between the technologies and transition variables of features. The individual technology modules are to be combined to generate feature-specific technology chains for the manufacturing of individual features. An exemplary technology module for the technology high velocity oxygen fuel (HVOF) spraying to coat surfaces of cylinder bores is depicted in Fig. 6.

The top of the module contains information about the feature to be manufactured by the technology (feature F1: cylinder bore). On the left side of the technology module, relevant input variables are listed. These input variables can influence the applicability of the technology or they can affect the output state of transition variables. For instance, the transition variable geometry can have an influence on the applicability of the HVOF spraying technology (compare Fig. 6). If the geometry prevents the positioning of the tool (in this case the HVOF nozzle) the technology HVOF spraying cannot be deployed.

The center of the technology module provides additional information which is necessary for the application of the

Fig. 4 Change of secondary variables due to direct technology impacts or side effects

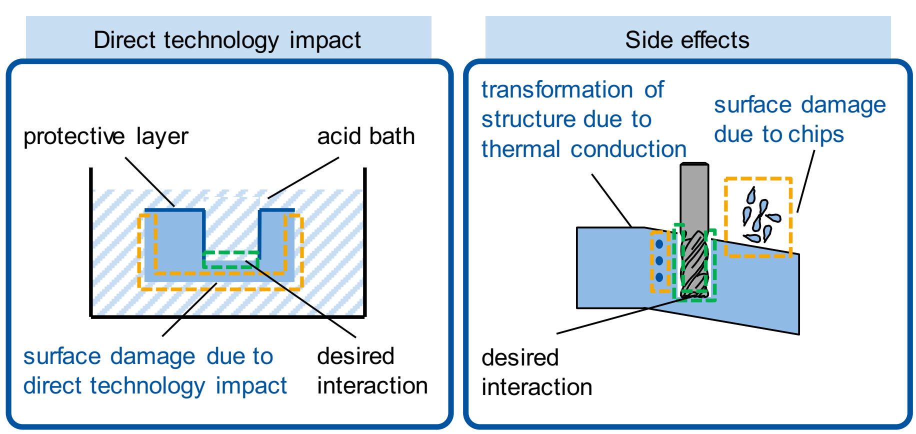

Fig. 5 Interactions between technologies and transition variables of features

feature F1	primary transition variables	secondary transition variables: due to direct technology impact		secondary transition variables: due to side effects	
		feature	effect on variables	feature	effect on variables
milling	modification of macro geometry	F1	new surface roughness	F2	surface damage caused by hot chips
	…	F2	modification of macro geometry	F3	deformation caused by residual stresses
	...	...	...	...	...
drag finishing	reduced surface roughness	F1	rounding of edges	F3	surface damage caused by fixation
	...	F2	reduced surface roughness	...	...
	...	F2	rounding of edges	...	...
	...	...	...	...	...
A	B	C	D	E	F

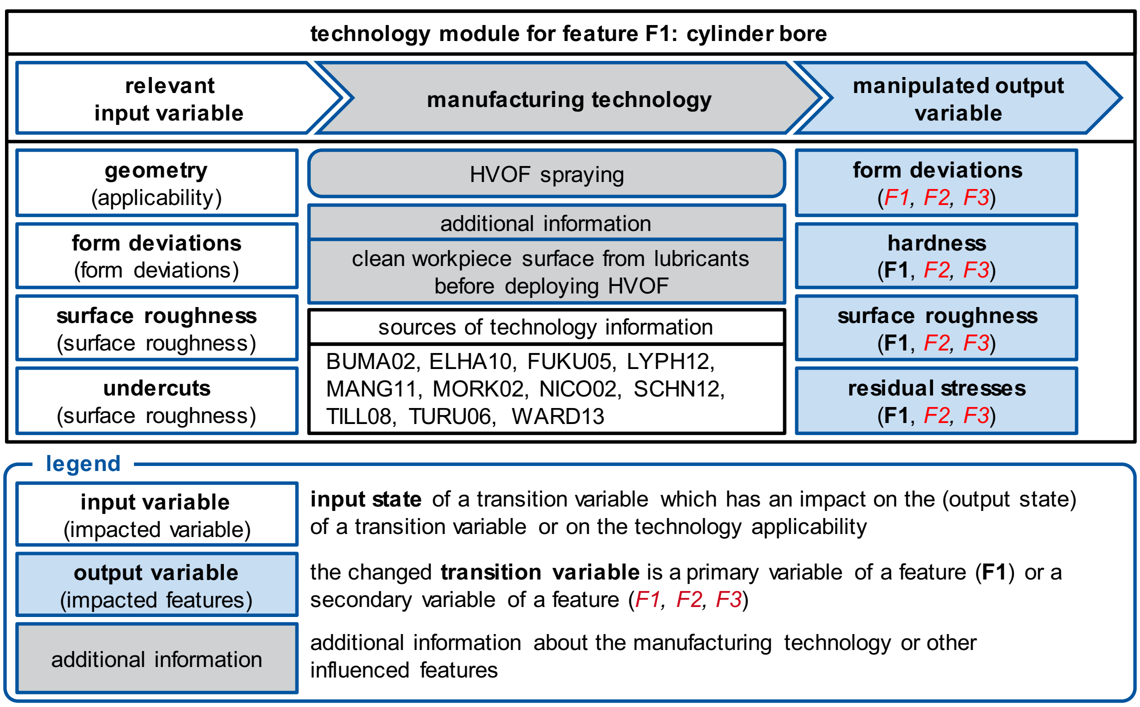

Fig. 6 Exemplary technology module of high velocity oxygen fuel (HVOF) spraying. (Color figure online)

technology. Furthermore, it contains the sources which were used to generate the technology module. As shown in Fig. 6, the removal of lubricants is necessary for the application of HVOF spraying [15].

The right side of the technology module contains a list of all transition variables which are changed if the technology is deployed. The technology module contains a distinction between primary and secondary variables. If a primary variable of a feature is changed, the feature is written in bold (hardness [16], surface roughness [15] and residual stresses [17] of feature F1). If a secondary variable is changed it is marked red (form deviations of features F1, F2, and F3 as well as hardness, surface roughness and residual stresses of features F2 and F3) [18]. After the generation of all technology modules, possibilities of combining them to design feature-specific technology chains are described in the next step.

3.1.5 *Feature-specific technology chains*

The term feature-specific technology chain is introduced to describe a technology chain which is capable of manufacturing an individual feature. Such technology chains are designed in this step by combining the previously identified capable technologies.

The design process for technology chains presented in this paper requires the consideration of quantitative information about relevant input variables and changed output variables of the investigated technologies. Since no specific machines are considered this quantitative information needs to be estimated for each considered technology. In order to make valid estimations about technology capabilities, expert knowledge and explanatory models from scientific literature are to be considered. Values of input and output variables need to be matched at technological interfaces. Technological interfaces describe the following relation between technologies: In a technology chain, the output of a technology is equivalent to the input of the succeeding technology. Thus, the output state of transition variables after the application of a technology i is identical to the input state of transition variables for the succeeding technology i + 1 [6]. Individual technologies can be combined for the manufacturing of a feature if the values of the machined output variables of a technology match the values of the relevant input variables of another technology which is to be applied afterwards (Fig. 7, top). If these values do not match, both technologies cannot be in a direct predecessor–successor relation. After the application of the last technology of the chain, all values of transition variables of the manufactured feature lie within the set of acceptable values of transition variables (compare Fig. 2). The result of this step is a set of technology chains, which contains at least one technology chain for the manufacturing of each feature.

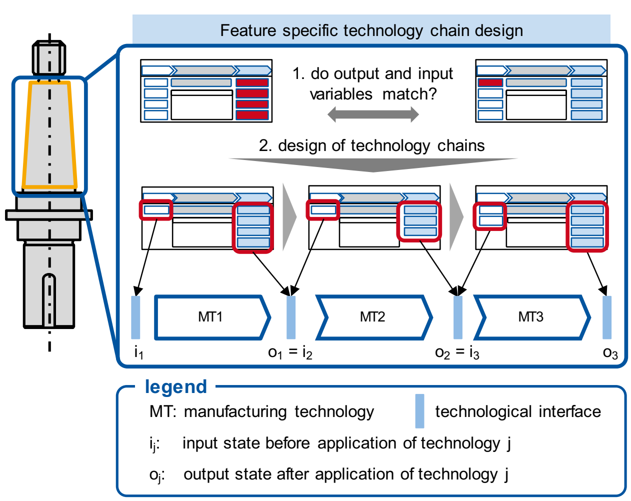

Fig. 7 Design of feature-specific technology chains in reference to [6]

3.2 Product-oriented point of view

3.2.1 *Constraints in sequencing the feature manufacturing*

After the definition of theoretically feasible feature-specific technology chains, constraints regarding the sequence of manufacturing features are identified. For example, a feature "screw thread" requires a feature "bore hole" as its predecessor. Sequencing constraints are shown in a feature–feature–matrix according to [2] (Fig. 8).

If a feature requires a predecessor, the considered feature itself is automatically a successor. Therefore, the feature–feature–matrix is skew-symmetric. The letter "P" in the feature–feature–matrix means that the relative feature must be manufactured before the initial feature. The letter "S" means that the relative feature must be manufactured after the initial feature. A "0" indicates that no constraints regarding the sequence of manufacturing exist between the features. All constraints regarding the sequence of feature manufacturing are depicted in the feature–feature–matrix. The right side of Fig. 8 contains potential sequences in which the features can be manufactured. These sequences are derived from the feature–feature–matrix. In the example in Fig. 8, feature F1 must be manufactured first and feature F4 must be manufactured second. There is no sequencing constraint between features F2 and F3.

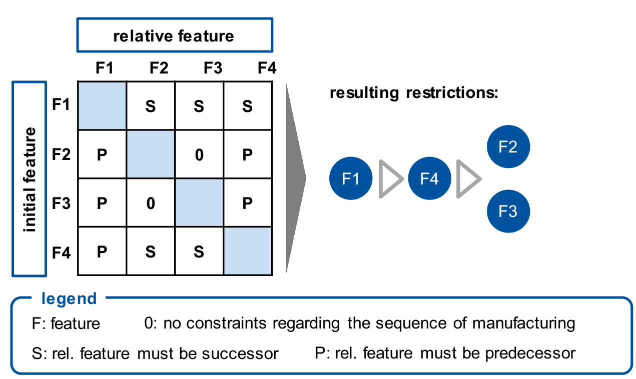

Fig. 8 Exemplary feature–feature–matrix in reference to [2]

3.2.2 Constraints in sequencing technologies

Constraints concerning the sequencing of technologies are visualized in a technology–technology–matrix according to [19]. It contains predecessor–successor-relations between technologies (Fig. 9). For example, coating a substrate by plasma spraying requires a roughening process to be deployed on the substrate previously. Information about constraints in technology sequencing can be derived from scientific literature and from the previously presented technology modules (Fig. 6).

In the example in Fig. 9 technology MT1 is a required predecessor of technologies MT2 and MT6. Technology MT2 cannot be applied after technology MT3 and technology MT3 must be applied after MT6. Technology MT4 can neither be applied before MT3 nor after MT5.

initial technology \ relative technology	MT1	MT2	MT3	MT4	MT5	MT6
MT1		0	0	0	0	0
MT2	P		0	0	0	0
MT3	0	¬S		¬P	0	0
MT4	0	0	0		0	0
MT5	0	0	0	¬S		0
MT6	P	0	S	0	0	

legend
MT: manufacturing technology
0: no constraints between technologies
S: relative technology must be successor
P: relative technology must be predecessor
¬S: relative technology cannot be successor
¬P: relative technology cannot be predecessor

Fig. 9 Exemplary technology–technology–matrix in reference to [19]

3.2.3 Final technology chain design

Technology chains for the manufacturing of individual features were designed in previous steps. The top of Fig. 10 depicts how such technology chains are sequenced so that they comply with the constraints derived from the feature–feature–matrix in Fig. 8.

Technology chains which comply with the constraints derived from the feature–feature–matrix are generated. If a technology is used to manufacture more than one feature, it is investigated if those features can be manufactured in one manufacturing step (Fig. 10). This can lead to a relaxation of sequencing constraints from the feature–feature–matrix if features which were planned to be manufactured successively are then manufactured in the same step. The resulting sequences of manufacturing technologies are preliminary technology chains for the product manufacturing.

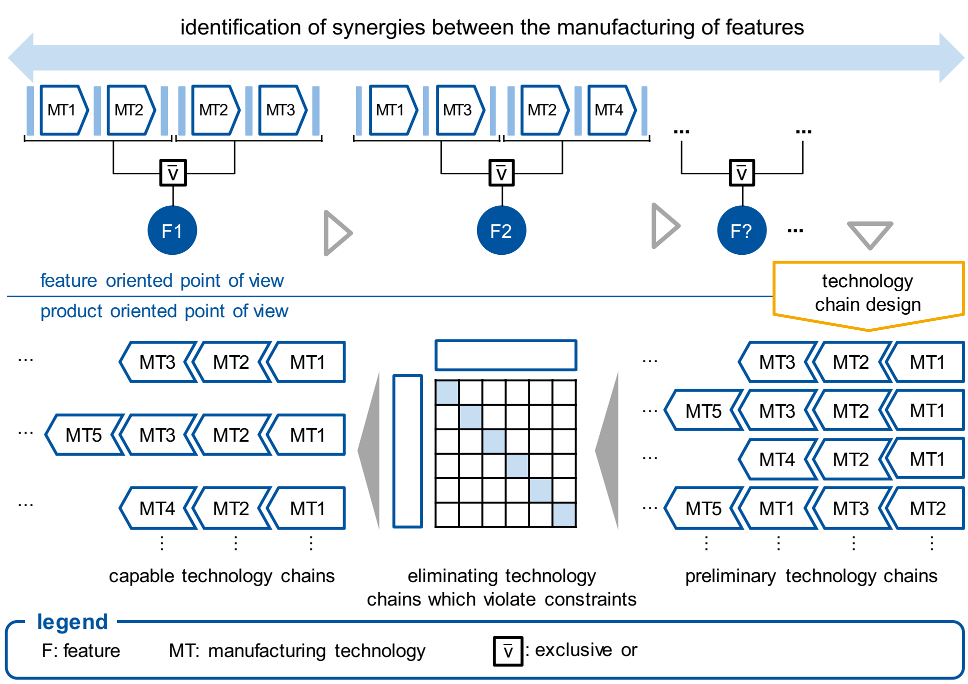

Fig. 10 Identification of feasible technology chains

After the design of preliminary technology chains, constraints regarding technology sequencing are considered. All preliminary technology chains, which violate constraints derived from the technology–technology–matrix, are eliminated (Fig. 10, bottom center). In the example in Fig. 10, one technology chain is eliminated because it violates the constraint of MT1 being a mandatory predecessor of MT2. The remaining technology chains are capable of manufacturing the considered product (Fig. 10, bottom left). In a subsequent step, a specific capable technology chain is to be selected. The selection process is not included in the presented methodology. However, different approaches concerning the selection of a specific technology chain can be found in [20].

4 Case study from the automotive industry

In this chapter, the previously presented methodology is applied to a ramp-up case from the automotive industry. During productions ramp-ups the introduction of new technologies can cause significant delays due to undesired process interactions [21]. The possible deployment of a new technology chain for crankcase manufacturing is investigated. For the purpose of illustrating the application of the methodology, a simplified case is considered. The object of reference is a cylinder bore of the crankcase and its adjacent surface and volumetric elements. The focus of the case study is on the identification of secondary transition variables (compare Fig. 4) and undesired process interactions.

4.1 Definition of features

The first step of the methodology is the definition of features. In order to define features, functions and surface or volumetric elements of the considered product were identified. Subsequently, functions were assigned to surface and volumetric elements.

The identified functions of the cylinder bore are providing a guidance for the piston (Fn1) and transport of lubricating oil (Fn2). Additionally, two manufacturing requirements were identified. These requirements are assuring the mountability of the piston (Fn3) and providing a basis for the installation of the cylinder head gasket (Fn4). In order to define the features of the cylinder bore, these functions and manufacturing requirements were assigned to surface and volumetric elements of the crankcase. A schematic drawing of the crankcase and the assignment of functions to its surface or volumetric elements is shown in Fig. 11.

Both functions (Fn1, Fn2) are fulfilled by the running surface (S1), the run-in-chamfer (S2) enables the mountability of the piston (Fn3) and the separation surface (S3) provides a base for the installation of the cylinder head gasket (Fn4).

The next step of the methodology is the definition of the required value range of the features' transition variables (compare Fig. 2). An analysis showed that a low roughness (Rz ≤ 6 µm) and high hardness (H ≥ 500 HV) of the running surface are required. Additionally, the run-in-chamfer has to be free of burrs and with minimal form deviations at the transition to the running surface. The separation surface is required to have a roughness of Rz ≤ 15 µm. After the definition of features, capable manufacturing technologies were identified in the next step.

4.2 Identification of capable manufacturing technologies

The casting technology *pressure die casting* was chosen to manufacture the aluminum base body of the crankcase. *Electroplating* and *high velocity oxygen fuel (HVOF) spraying* were identified as capable coating technologies. HVOF spraying requires a preprocessing of the running surface via *mechanical roughening* [15]. *Honing* was chosen as a finishing process to generate groves in the coated running surface. These groves enable the transport of lubricating oil. The identified capable technologies are depicted in Fig. 12.

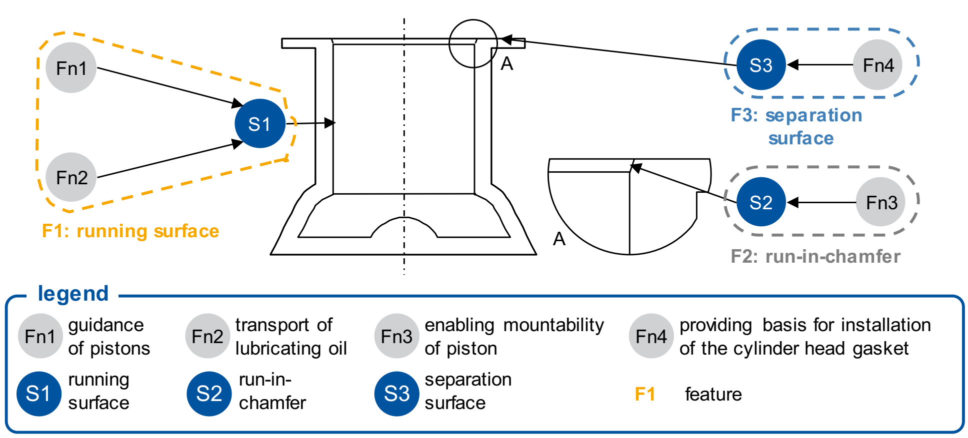

Fig. 11 Definition of features of a cylinder bore

4.3 Identification of secondary transition variables

The next step of the methodology is the identification of secondary transition variables. The process of identifying secondary transition variables is exemplarily shown for the technologies mechanical roughening and HVOF spraying. Literature research and expert interviews were conducted in order to identify secondary transition variables of the technologies HVOF spraying and mechanical roughening. An excerpt of the results of the research is exemplarily shown in Fig. 13.

Both considered technologies can have an effect on secondary transition variables. The mechanical roughening process can lead to form deviations and surface roughening on the run-in-chamfers. The HVOF spraying process can have an undesired effect on the form, roughness and hardness of the cylinder bores or adjacent features [18]. After the identification of these interactions, countermeasures to be taken, if these interactions cause a worsened production result, can be derived in a subsequent step. The identification of countermeasures is not included in the methodology and is the objective of future research. Counter measures can for example be logically deduced by analyzing the process with experts or they can be deduced from existing explanatory models in scientific literature.

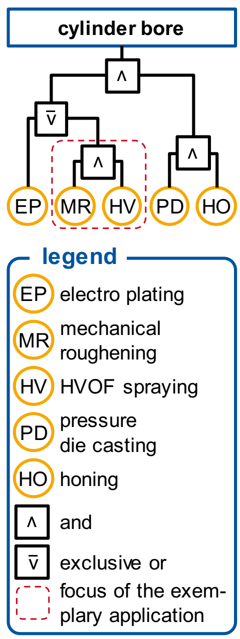

Fig. 12 Capable technologies for cylinder bore manufacturing (simplified)

5 Summary and outlook

This paper presents a feature-based approach to design technology chains under consideration of undesired interactions in the technology chain. Firstly, features are defined as a combination of functions and physical product elements. Then, technologies which are capable of producing those features while meeting the required manufacturing tolerances are identified. For the identified technologies it is investigated if interactions between the features and the manufacturing technology lead to unintended effects on feature characteristics which are not supposed to be influenced by the considered technology. These so-called

Fig. 13 Interactions between technologies and transition variables in cylinder running surface roughening and coating (excerpt)

running surface	primary transition variables	secondary transition variables			
		due to direct technology impact		due to side effects	
		feature	impact on variables	feature	impact on variables
mechanical roughening	roughened surface	run-in chamfer (F2)	induced form deviations	run-in chamfer (F2)	impact on roughness caused by hot chips
	generated undercuts			run-in chamfer (F2)	impact on roughness due to reaction with lubricant
HVOF spraying	reduced surface roughness	cylinder-bore (F1)	form deviations due to inhomogeneous coating application	run-in chamfer (F2)	impact on form due to high process temperatures
	increased hardness	release surface (F3)	impact on form, roughness and hardness due to sticking coating	run-in chamfer (F3)	impact on form due to high process temperatures

undesired process interactions are summarized in technology modules which are generated to describe the impact of each manufacturing technology on the features. The technology modules are used to generate individual feature-specific technology chains. Afterwards, technology chains for the manufacturing of the whole product are generated by combining the feature-specific technology chains. During the step of combining feature-specific technology chains, synergies between the individual technology chains are identified and used to combine manufacturing steps whenever it is feasible. A case study from the automotive industry showed that the methodology can be used to identify feature-specific technology chains and that it enables the user to identify the undesired process interactions.

The new feature based approach for technology chain design presented in this paper enables the user to systematically identify undesired interactions between technologies and the manufactured features. Deploying the presented methodology enables the design of robust technology chains, which leads to fewer defective parts and thus to an improvement of the produced parts' quality. The ability to identify undesired interactions a priori enables the user to deduce countermeasures before a production ramp-up begins, which can lead to a significant reduction of the overall process time as idle times can be avoided.

Future research will focus on the process analysis of individual technologies to identify reasons for the occurrence of undesired process interactions. Additionally, the systematic identification of countermeasures to be taken against undesired process interactions as well as a concept to include inspection planning in the methodology will be addressed. Furthermore, a computer-supported approach to enable an automated time-efficient technology planning process based on the presented methodology is to be investigated.

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