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OPERATIONALIZATION OF MANUFACTURING RESTRICTIONS FOR CAD AND KBE-SYSTEMS

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1. Introduction

Besides the fulfilment of functional and (aesthetic) design requirements the shape of a product is determined by the used manufacturing processes. Regarding the product development process, it is advantageous to consider these influences at a very early stage [Pahl and Beitz 1997]. However, for many reasons this simple view on the development process has become invalid. On the one hand, the huge variety of different manufacturing techniques with their partly very special design requirements and restrictions is difficult to overview [Boothroyd 1996]. On the other hand, the sophistication of manufacturing techniques is still increasing and offers e.g. potential for near-net shape geometry using processes like precision forging [Bach and Kerber 2014] or additive manufacturing [Lachmayer et al. 2016].

1.1 Motivation

Design guidelines for different manufacturing techniques have already been discussed for decades. Furthermore, approaches like Design for Manufacture and Assembly (DFMA) proved their impact in context of concurrent engineering [Huang 1996]. However, the exploration and limitation of the possible design solution space is dependent of the designer's experience and his ability to make design knowledge explicit since a lot of guidelines is formulated as implicit heuristics. Regarding the implementation of explicit manufacturing knowledge into digital product models different aspects have been presented for various disciplines. E.g. Xuewen discusses the use of design rules in IF-THEN-ELSE notation or decision tables for forging designs [Xuewen et al. 2003]. Other authors debate the design of computer-aided tools for fixture design which use different techniques of knowledge-based-engineering (KBE) systems [Boyle et al. 2011]. Nevertheless, up to date no general framework for the implementation of manufacturing knowledge into 3D-CAD-models can be found. In this article a part of this gap is bridged.

1.2 Structure of the paper

In the following section 2 the basic use of manufacturing restrictions within the design process is derived. As there are many possible theories this concept might be implemented in, like Gero's Function-Behaviour-Structure-ontology, we focussed on a design theory that already integrates the possibility of restricting the design solution space with certain preconditions. Here, the Characteristics-Properties Modelling/Property Driven Development (CPM/PDD) design theory of Weber [2005] is chosen since it allows generally the formulation of restrictions as so called external conditions. Based on view and wording of the CPM/PDD, different classification criteria for structuring these restrictions are presented in sections 3 and 4. The resulting design catalogue, which is presented in section 5, allows the deduction of methods how to operationalize and model single restrictions in a CAD-system. In this context operationalization means on the one hand the explicit formulation of manufacturing restrictions like "good castability" in terms of parameters or design rules a CAD-system can handle and on the other hand an implicit formulation which is based on validation in analysis systems. Therefore, different KBE techniques are used and visualized for an extrusion profile in section 6. The final section 7 then summarizes the paper and drafts further research questions.

2. CPM/PDD design theory

The CPM/PDD design theory introduced by Weber can be used for all different design activities like new, adaptive and variation design. It is based upon the distinct differentiation between characteristics (parameters of product an engineer can directly take influence on, e.g. shape, dimensions, material) and properties (aspects of the design which cannot directly influenced, e.g. moments of inertia, weight or the fulfilment of a certain stress distribution). This separation allows two different relations between characteristics and properties in the design process. At first, synthesis is understood as modification of a product's characteristics whereby its properties are influenced and converged to the requirements. Secondly, analysis is the examination of a product's behavior and the verification that it matches the targeted requirements. So, the design process may be described as multiple synthesis-analysis loops which are considered as closed-loop control circuit. With every loop the design evolves towards the targeted requirements [Vajna et al. 2009]. The differentiation between characteristics and properties is also reasonable regarding the use of computer-aided-design and -engineering applications. E.g. product models in CAD-systems are usually set-up via characteristics and their inter-dependencies. For the analysis of properties other CA-systems (e.g. FEM or CFD) are necessary.
As third element of the CPM/PDD the so called external conditions (EC) are modelled. EC are used to restrict synthesis and/or analysis operations with regard to all impacts which externally influence the design process (e.g. availability of manufacturing facilities, design interfaces of neighbor parts, etc.).

3. Modelling of manufacturing boundary conditions as EC

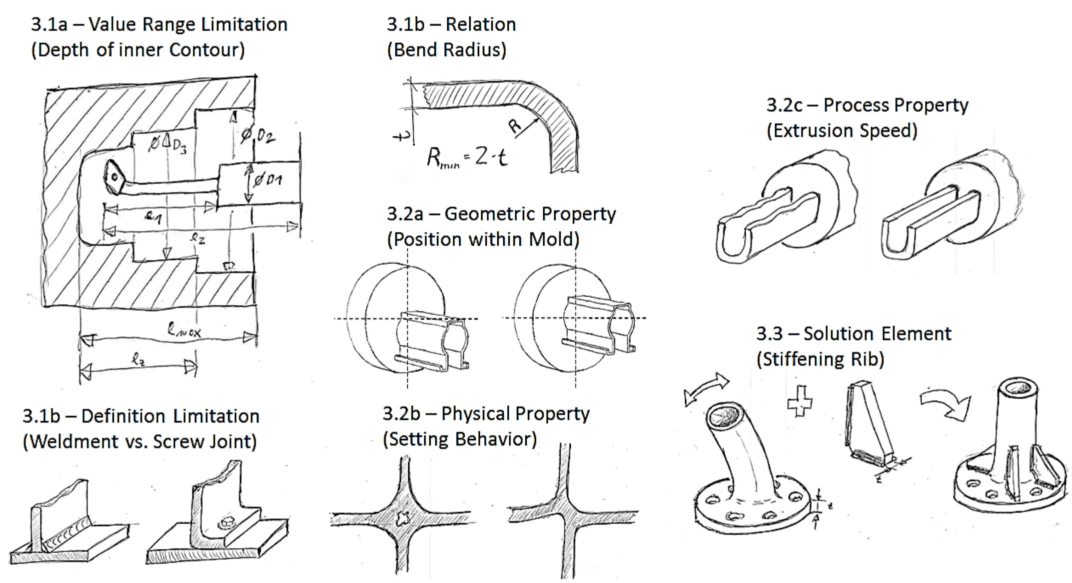


Figure 1. Different types of manufacturing restrictions

Guidelines like e.g. DFMA or explicit manufacturing restrictions like a minimal bend radius are commonly formulated for certain applications to limit the design space the engineer can operate in. To get a deeper understanding of the inter-dependencies between characteristics, properties and EC like introduced above, different types of restrictions are analysed and illustrated in this section. An overview is given in Figure 1.

3.1 Restrictions of characteristics and dependencies

Restrictions of characteristics have to be considered during synthesis. Basically three different restriction types can be formulated:

(a) Limitation of a characteristic's value range:

This type of restriction is usually based on explicit design knowledge and can easily be used during the synthesis since the value has to be checked against the possible value range. The range itself can either be restricted by upper and lower limits or by a list of permitted values. Examples are sizes of transport containers, travelling distances of a milling machine or thread diameters resulting from available tools or standard parts.

(b) Limitation of characteristics definition:

The majority of heuristics for DFMA specifies a manufacturing related way to define characteristics. This type of restrictions is more abstract, e.g. like the definition of mold release slopes in cast design or the avoidance of accumulations of weld seams. A different group within that restriction type is set-up by the determination of the product architecture (integral, differential, modular) and the resulting design interfaces which have to be already considered in an early design phase. As depicted above, a welded connection and a bolted connection have different parameter sets.

(c) Restriction of dependencies:

This class of restrictions refers to dependencies between two or more characteristics which can be expressed as logical or mathematical relations. An example is the bending radius in sheet metal design which usually is related to the sheet thickness via decision table or equation.

3.2 Restrictions of properties

In addition to the above, some design guidelines cannot be directly used for synthesis, because a product's characteristics or their dependencies are not directly addressed by the guideline. Nevertheless, if such a guideline has any relation to the product's properties in general it can be used for design verification by analysis. Based on the analysis type the following differentiation is proposed:

(a) Restriction of geometric properties:

In contrast to geometric characteristics, geometric properties result from adjacent design activities like tooling or fixture design so that they may be used for analysis of the current design. E.g., a guideline for extrusion molding advices to concentrate material in the center of the extrusion mold in order to improve the forming process. Here, a direct synthesis operation can’t be carried out, but an evaluation of the material distribution by consideration of the tool design and a feasibility analysis is realizable. In the following design loop the geometric characteristics can be optimized then.

(b) Restriction of physical properties:

In other cases, a driver for design is a product's physical properties that impact e.g. on process stability or the manufacturing quality. E.g. regarding casting, design guidelines help in minimizing residual stresses after casting. Here, the heat conduction property of the part has to be homogeneous in relation to the casting process boundaries. This can usually be determined via simulation in an analysis step since analogues models only are applicable for simple geometries. Note, that adjacent design activities like mold or fixture design may have a severe impact on such restrictions [Boyle et al. 2011] since in the above mentioned example additional heaters or coolant ducts influence the setting behavior of the casted part.

(c) Restriction of process properties:

Furthermore, there are restrictions which result from the manufacturing process itself. Geometric properties as well as the stability of the manufacturing process are depending on process parameters which only can be examined by simulation in an analysis step. E.g. referring to hydro forming the amount and location of apertures is determined by the maximum pressure loss the process can support. Another example is the extrusion speed of the corresponding process since it influences the quality of the extruded profile.

3.3 Restriction of solution elements

Besides the synthesis and analysis related design guidelines there are also guidelines which can be represented by a solution element/pattern. According to the CPM/PDD theory the guideline consists of predefined synthesis and analysis operations with distinct input/output characteristics and properties.
Solution elements/patterns often address special functional properties which also can be process related. E.g. regarding extrusion molding, there are elements for corner stiffening of hollow profiles. The geometric characteristic's definition as well as the value ranges is predefined by the related guideline in a way that manufacturing is supported ideally. By using such elements the stiffness of the part will be increased.

4. Mapping of manufacturing restrictions on design parameters

Summarized, it was pointed out that guidelines like DMFA and the related manufacturing restrictions have several inter-dependencies with the product definition (characteristics and dependencies), the design process (synthesis and analysis) and the product properties. Because of the importance of the synthesis related formulation of such restrictions during the design process, a further differentiation is presented to support an operationalization of design boundaries. Thus, the classification of characteristics supports the allocation of specific manufacturing restrictions to product characteristics and later to parameters in CAD-modelling. In the design methodology literature there exists a commonly used classification introduced by Roth [2001] and Koller [1998] for design parameters which can directly be used for this aspect. This classification groups the design parameters defined, varied or deleted by synthesis in the following way:

- Topology: Parameters describing the inner structure of a part are related to this group. From a mathematical point of view the topology defines the number of invariant regions of a part definition, e.g. the number of holes in a profile.
- Dimensions: All parameters which define dimensional characteristics of a part, like length or angle dimensions are related to this group. Depending on the topology this parameters are the framework for the parameters and dependencies of the following parameter groups.
- Shape: Roundings, fillets and special designed surfaces of a part – commonly described as shape or contour – append several design parameters to characteristics.
- Number of elements: Focusing shape elements which special functional properties there are parameters to describe the number of such elements, e.g. the number of sprockets of a gear or the amount of stiffness ribs of casting parts.
- Tolerances: In addition to the solid definition of a part there are tolerances for dimension, position and shape. Related to manufacturing this group is also important because for the definition of tolerances the capabilities of the manufacturing technology have to be considered and may e.g. have severe impact on the stiffness properties of a welded machine base.
- Technical Surface: Surface quality regarding roughness, orientation of grooves or surface hardness also belong to the group of attributive design parameters which are not explicitly modelled e.g. in CAD. Nevertheless, manufacturing capabilities impact on their definition.
- Material: Finally there is the definition of material which includes the determination of the corresponding physical properties like density, modulus of elasticity, etc.

The term parameter here is used in order to distinguish between this classification and the classification of characteristics and properties of the CPM/PDD.

5. Collocate restriction by design catalogue method

All characteristics of a part or component can be classified into the above groups. Nevertheless, an adequate operationalization still needs a more detailed classification. To those criteria belong:

- Application: This defines whether restrictions or solution elements are applied for synthesis, analysis or both.
- Locality: For operationalization the effective range of restrictions is significant which can be either local or global. Referring to the later use in CAD, the first means that only single features or contours are affected, and the latter means that the whole part is influenced.
- Application condition: Evaluation of the aspect if a boundary is mandatory or sufficient/optional.
- Formulation: The kind of mathematical formulation, either explicit, implicit or heuristic. In this context, explicit means that a restriction is expressible as e.g. physical relation, as decision table or If-Then-Rule. Implicit stands for restriction which have to be represented e.g. by analogous models or the validation with analysis tools. Heuristic as last type of formulation is the storage of knowledge within templates. Here, solutions for best-practise applications can be modelled without naming each single restriction.
- Impact to process properties: The relative impact to specific properties of the manufacturing process like stability or feasibility is weighted.
- Impact to product properties: The relative impact to typical product properties like durability or stiffness in relation to common used applications is evaluated as well as geometrical properties.

As a first step for operationalization of manufacturing restrictions it is recommended to collect the restrictions of a defined technology – in this paper exemplified by extrusion molding – in a design catalogue using the presented taxonomy as classifying criteria. Design catalogues have to be understood as collections of design related knowledge and may include physical effects, solution principles, machine elements, etc. [Franke et al. 2004]. The framework of such catalogues consists of three basic parts. First, classifying criteria serve as a structure for the content of the catalogue. Secondly, in the main part the single solutions are depicted as drawings, sketches, equations, etc. Finally, the given solution and selection characteristics allow the systematic selection of distinct solutions based upon the requirements the designer has to meet.

In Figures 2 and 3 a design catalogue for restrictions regarding extrusion molding is depicted. The first column contains the influence of external conditions, the second the classification of design parameter groups as classifying criteria. In the main part the restrictions itself are illustrated while as selection criteria for operationalization of the single restrictions are implemented as mentioned above.

6. Operationalization of manufacturing restrictions

In order to use restrictions not only as a concept of proof in the design process the implementation of such knowledge in synthesis via virtual prototypes like CAD-models is a possibility to shorten development times and raise the quality of design results. Basically, regarding CAD this can be done through KBE. Basis for the utilization of KBE-techniques is the application of parametric CAD. There are three major benefits from using parametric design in opposite to rigid geometry [Shah 2001]:

1. Automatic change propagation
2. Geometry re-use
3. Embedding of design/ manufacturing knowledge with geometry

It is commonly accepted that the parameterization of a virtual prototype leads to the individual description of the geometry and its defining parameters and constraints which is advantageous for the above mentioned view on characteristics and design parameters.

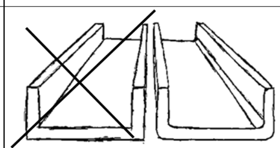
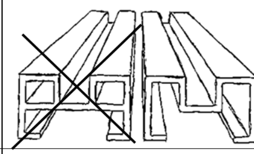
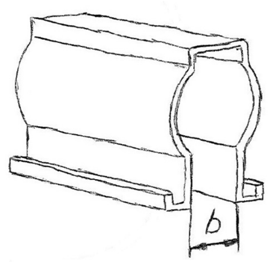
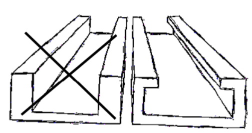
Classifying Criteria			Main Part			
1	2	3	External Condition	Sketch	Included Geometry Parameters	Explanation
Design Operation	Type of Geometry Parameter					
Definition of Characteristic Value Range	Geometry	Topology				
		Dimension	Minimum Radius		Radius	All edges must have a Radius of min. 0.5 mm
		Shape				
		Quantity				
		Tolerance				
		Surface				
	Material	Type of Material				
		Type of Treatment				
Definition of Characteristics	Geometry	Topology	Solid profiles should be prefered over hollow profiles.			Lower cost for tools.
		Dimension				
		Shape				
		Quantity				
		Tolerance				
		Surface				
	Material	Type of Material				
		Type of Treatment				
Definition of Dependencies	Between Geometry Parameters	Dimension - Shape	Complex channel geometry: $A < 3*b^2$. (A: Area of channel)		Length and width of channel.	Less tool stress.
		Dimension - Dimension	Uniform wall thickness.		Wall thickness	Less tool stress.
		Dimension - Topology				
		Dimension - Quantity				
		Shape - Dimension				
		Topology - Quantity				

Figure 2. Collocated restrictions for extrusion molding in a design catalogue

Selection Characteristics											
Application	**Locality**	**Characteristic**	**Formulation**	**Impact on Process Properties**			**Impact on Product Properties**				
				Stability	**Feasibility**	**...**	**Strength**	**Rigidity**	**Mass**	**Quality of Geometry**	**...**
synthesis	global	mandatory	explicit		big			big		big	-
synthesis	global	sufficient/ optional	implicit		small			big	small		
synthesis	local	sufficient/ optional	implicit		big		big	big	small	big	
synthesis	global	sufficient/ optional	implicit		moderate		big	big	moderate	big	

Figure 3. Collocated restrictions for extrusion molding in a design catalogue

In the remainder of this section different formulations of manufacturing restrictions expressed by KBE-principles are exemplarily derived from the solution characteristics of the restriction catalogue. For a detailed review and presentation of state-of-the-art KBE-modelling principles in CAD-systems refer to [Gembarski et al. 2015].

6.1 Rules and decision tables

Basically, the rule concept is grounded upon the IF-THEN-ELSE-notation known from software development. Rules are fired procedurally and can be used to execute subordinate rules or delete them temporarily from the working memory. The rule concept is very well known as reasoning mechanism of the expert systems from the 1980's [McDermott 1982] and can be easily used as design rules to determine parameter values [Tang et al. 1988], [Ravi et al. 2003] or topological parameters (i.e. the suppression state of design features). A decision table is an aggregation of design rules that have the same context but different value ranges. Generally disadvantageous is the maintainability if the rules get to numerous and have to interact with each other.
Thus, applied on the restriction catalogue, rules should be used when the influence of the corresponding characteristic is only local and its formulation for synthesis is of type explicit. E.g. when it is necessary to enclose a sharp-edged component within a hollow profile the edge of the profile cannot be rounded as it is normally recommended. So, the rule may be formulated as: "IF face1 AND face2 are used as effective areas for sharp edged components THEN insert cut".

6.2 Constraints

The application of constraints is very common in CAD systems. A model's parameters usually are linked by arithmetical or logical constraints. Another class of constraints is geometric ones, like setting two sketch lines parallel to each other or placing a component's connection point coincident on the origin of an assembly. The use of constraints allows a more simple formulation compared to rules and is easier for maintenance.
So, regarding the restriction catalogue constraints may be used when the characteristic's influence is global and can be formulated explicitly. E.g. when addressing the minimum edge radius all corresponding feature can be linked arithmetically with a global variable Rmin.

6.3 Parameter plans

The parameter plan is a notion that is based on the constraint concept. In the sense of a solution element like mentioned above, a predefined CAD-sketch with predefined parameters and dimensions is used to make implicit design knowledge explicit for application on local areas. This is depicted for the extrusion profile below (Figure 4). With respect to the catalogue, such formulation of restrictions may be applied, when the impact is local and the type of knowledge is explicit.

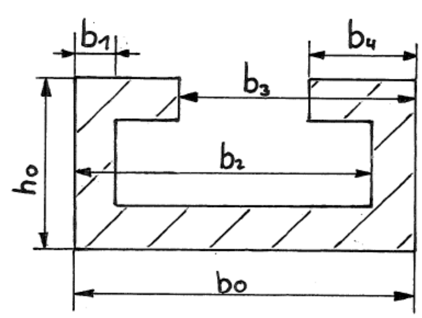


Figure 4. Example of an intersection for an extruded profile

In order to preserve the topology of the profile the following mathematical constraints have to be fulfilled:

$$0 < \underline{b0} < \infty \quad (1)$$

$$0 < \underline{b1} < (b0 - b3) \quad (2)$$

$$(b0 - b4) < \underline{b2} < b0 \quad (3)$$

$$b4 < \underline{b3} < (b0 - b1) \quad (4)$$

$$(b0 - b2) < \underline{b4} < b3 \quad (5)$$

$$2b1 < \underline{h0} < \infty \quad (6)$$

To get an equal wall thickness for both vertical areas, another constraint has to be introduced:

$$b0 - b2 = b1 \quad (7)$$

Symmetry regarding the upper cut then is expressed by:

$$b0 - b3 = b4 \quad (8)$$

6.4 Mathematical analogous models

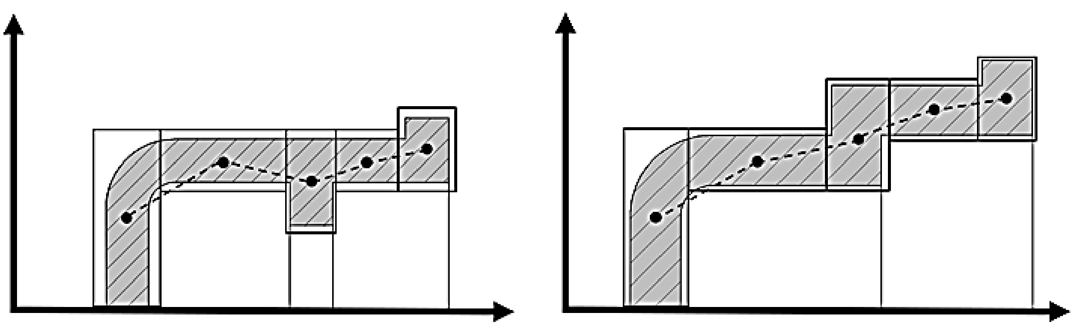


Figure 5. Monotony analysis of intersection segments

The formulation of mathematical analogous models is the most abstract and sophisticated KBE-modelling method and may be used for implicitly formulated restrictions that have global influence. E.g. in order to determine whether a contour is free of undercuts, it can be decomposed into single bounding boxes (rectangles) which centers of area are analysed if they are monotonically increasing (Figure 5).

7. Conclusions and outlook

In the present article, a framework for the implementation of manufacturing knowledge into 3D-CAD-models has been formulated. Therefore, those restrictions were characterized as external conditions in the context of the CPM/PDD development process. Based upon the classification of external conditions according to their influence on design parameters a restriction catalogue was set up and the different implementation methods using KBE-techniques were presented. Main driver for the choice of an according KBE-technique is the influence a restriction has either locally or globally and the type of knowledge which is used, either explicit or implicit.

The restriction catalogue is currently used to document all manufacturing restriction occurring in the processes examined by the collaborative research center 1153 "Process Chain for Manufacturing Hybrid High Performance Components by Tailored Forming".

However, guidelines for implementing the presented restrictions are still missing. This refers on the one hand on the formulation within a certain CAD-system since the abilities of implementing knowledge differ. On the other hand, it has to be examined to what extent such knowledge has to be implemented in digital prototypes regarding performance measures.

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