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USING MANUFACTURING TECHNOLOGICAL POTENTIAL IN PRODUCT DESIGN – A COGNITION-BASED APPROACH

M. Roos, S. Gramlich, H. Kloberdanz and M. Ćorić

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1. Introduction

Innovative manufacturing technologies are continuously being developed. Researching these new technologies leads to information and correlations that characterize a manufacturing technology, creating an ongoing increase in knowledge in the field of manufacturing technologies.
It is important to consider this knowledge of manufacturing technology during the product design process. A product designer is faced with the problem of deciding which information is necessary for a project and in which way the information can be used. To do this, several approaches were developed and became established. These approaches face the challenge of designing a product for a special purpose that also considers the restrictions caused by manufacturing technology. Manufacturing technology also has huge potential to create innovative products. Manufacturing technologies restrict the design of a product and create opportunities for designing innovative products. Using this potential during product design is ambitious and an appropriate approach is needed.

2. Manufacturing technology linear flow splitting

An example of an innovative manufacturing technology is linear flow splitting, which is used in manufacturing bifurcated sheet metal structures in an integral style [Jöckel 2005]. This manufacturing technology is of primary interest to researchers. Manufacturing processes are examined as well as manufactured products. This entails examination of the materials as well as component and system behaviour [Groche et al. 2012]. The manufactured products are characterized by manufacturing-induced properties. These are, for example, geometric properties, like the length of the flanges, material properties, like the strength in the forming zone, or properties that describe the hardness on the surface of the flanges [Groche et al. 2012] (Figure 1).

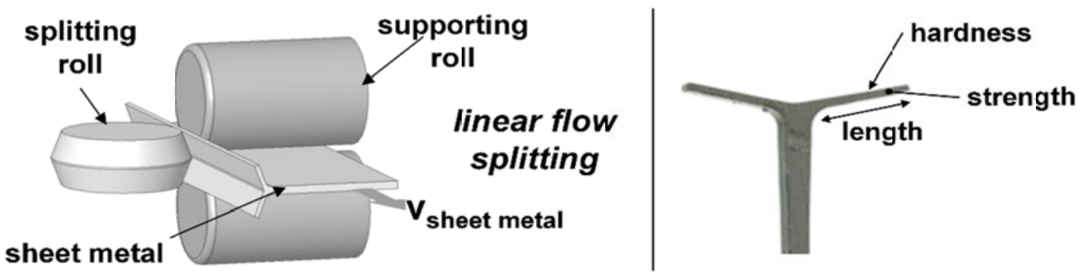


Figure 1. Linear flow splitting - process and product

3. Manufacturing aspects in classic PD approaches

There are a number of well-established product development (PD) approaches, such as the structured stepwise procedure, referring to the guideline VDI 2221 [1993]. Beginning with the project definition process, the development concludes with defining the product geometry and its material properties as part of the actual embodiment design. These geometric and material properties of the product can be documented in formats such as CAD data, component lists, etc. There is no explicit step that considers manufacturing aspects.

There are also PD approaches that use a different partition of the development process. Axiomatic design structures the product development process into four domains: customer domain, functional domain, physical domain and process domain [Suh 1998]. Consecutive domains are always related by two aspects. The first domain describes "what has to be achieved" and the second domain defines "how this need will be satisfied". The focus of axiomatic design in manufacturing is on the last domain; how the design parameters in the physical domain can be realized by processes described by process variables in the process domain has to be clarified [Suh 1998].

As part of the Design for X, manufacturing and other product life cycle processes or specific product properties are considered [Meerkamm et al. 2012]. Design for manufacturing (DfM) focuses on the manufacturing process and comprises approaches, methods and tools for considering manufacturing aspects in product design. The aim is to reduce processing times as well as costs by applying design measures without reducing product quality [Boothroyd et al. 2002]. Although there are a huge number of DfM approaches, methods and tools, they appear to lack homogeneity, with a varying level of detail. Using DfM mostly results in manufacturable solutions. It does not tap the potential of manufacturing technologies comprehensively.

Another approach is based on the model for integrated product and process development (IPPD). This model combines the process chains of product development, referring to the guideline VDI 2221, and product life cycle [Anderl and Melk 2005]. The designed product as output of the product development process chain is passed on to the manufacturing process. There is an additional exchange of information between both process chains. During the product development process information about the product life cycle processes is anticipated. In return, in designing a product, manufacturing and the other processes of the product life cycle are affected. Limited operationalization is an important issue in this approach. The way in which and which state of the PD process information about the product life cycle phases can be anticipated is not clearly defined.

4. Manufacturing technology for product design

A systematic approach for considering a manufacturing technology during product design has to ensure more than just the ability to produce a product; a comprehensive approach also has to provide the opportunity to tap the potential of a particular manufacturing technology. This goes beyond the scope of most previous approaches. Only thus can innovative products in a particular manufacturing technology be designed.

5. A new systematic cognition-based approach

A recent manufacturing integrated design approach is described in [Gramlich 2013]. This approach is based on a systematic and formalized description of technical products by their properties. It attunes product and process modelling. The aim of this approach is to enable holistic product innovations by utilizing the integrated correlation between product development and manufacturing processes. The manufacturing technologies that are used to realize manufacturing processes are characterized by manufacturing-induced properties. Specific manufacturing-induced properties are systematically integrated into the product design process to generate manufacturable solutions. This solution taps the potential of manufacturing technologies to fulfill the product function and generate additional functional benefit. Based on this approach, further details of the purpose of using manufacturing technological cognition during the PD process are elaborated.

5.1 Manufacturing technological cognition

Cognition is generated while developing and researching a specific manufacturing technology. In this context, manufacturing technological cognition can be understood as knowledge gained about a particular manufacturing technology.

Systematic preparation of the knowledge of a manufacturing technology in terms of cognition is indispensable. Because of the multiplicity of manufacturing technological cognition, a uniform way of preparing and integrating them into the product design process has to be determined. Therefore, a structured and formalized approach is necessary to specifically consider a manufacturing technology during product design.

The definition of cognition, in the context of cognition theory, is substantially equal to knowledge [Flach 1994]. Thus it is defined as the linkage of information [North 2011] (Figure 2). This linkage is particularly important for clarifying cognition. Hence, cognition is more than just information. It also describes correlations in the form of linkages. By defining the linkages, the way in which information could be used becomes clear. Due to this, cognition is more important to product designers than information. In PD especially, information about the products and the processes they pass are relevant. Thus, the definition of cognition is based on information dedicated to products.

As well as describing the linkage between information, cognition also gives some indication of the relevance and generality of the linkage. The relevance of cognition includes a statement about the importance of a linkage to the work of an expert. Not every linkage in information to a particular manufacturing technology could be used by an expert. The process of linear flow splitting, for example, is characterized by the geometry of the splitting roll as well as the necessary forces [Groche et al. 2012]. However, different materials with different thermal conductivities can be processed. Conductivity, as information about the manufactured product, is linked to further information about the process. Nevertheless, this linkage is not necessary to understanding the process of linear flow splitting. Thus, this linkage cannot be defined as cognition. Also the generality of a linkage has to be ensured. That means that a linkage which is found for one product has to be valid for similar products. Without an ensured generality a product designer could not further use the described linkage when developing new products.

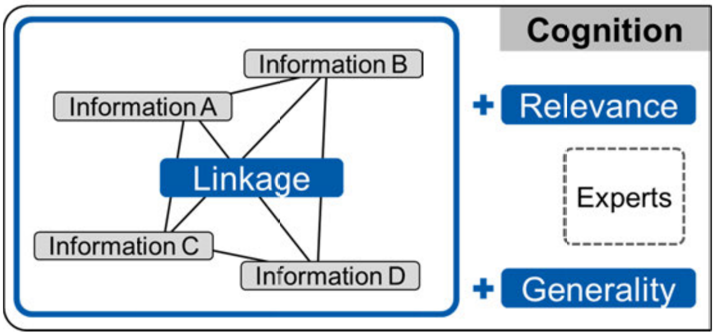


Figure 2. Criteria for cognition

Based on a particular manufacturing technology the defined terms could be extended to include manufacturing technological information and manufacturing technological cognition. Manufacturing technological information is information specific to a manufacturing technology. Manufacturing technological cognition defines cognition as made with a certain manufacturing technology in compliance with the mentioned criteria.

5.2 Essential steps of the cognition-based approach

Appropriate consideration of manufacturing technological cognition during product design requires pre-preparation for use by product designers. Therefore, a special procedure has to be defined.

The return of manufacturing technological cognition into the PD process contains the preparation of cognition and its deployment for product designers (Figure 3). This requires a formalization and structuring of cognition in two steps: the extraction of information and the linking of this information as the actual representation of correlations. The steps describing the return of manufacturing technological cognition are strongly based on the actual discovery process of cognition. Nevertheless the focus in describing this process is on clarifying the alignment and depiction of cognition in the models used during PD.

Besides the return, there is also a need to describe the integration of cognition into product development. By describing just the return it is not possible to understand the way in which manufacturing technological cognition can be used during product design. The integration contains different ways that product design can be affected by manufacturing technological cognition.

Summarizing the overall approach contains the systematic return and the systematic integration of manufacturing technological cognition into the product design process (Figure 3). The defined approach can be combined with an algorithm-based design approach as a specific example of PD approaches, as shown in Figure 3 [Groche et al. 2012]. Both approaches are mutually complementary in a structured and systematic procedure.

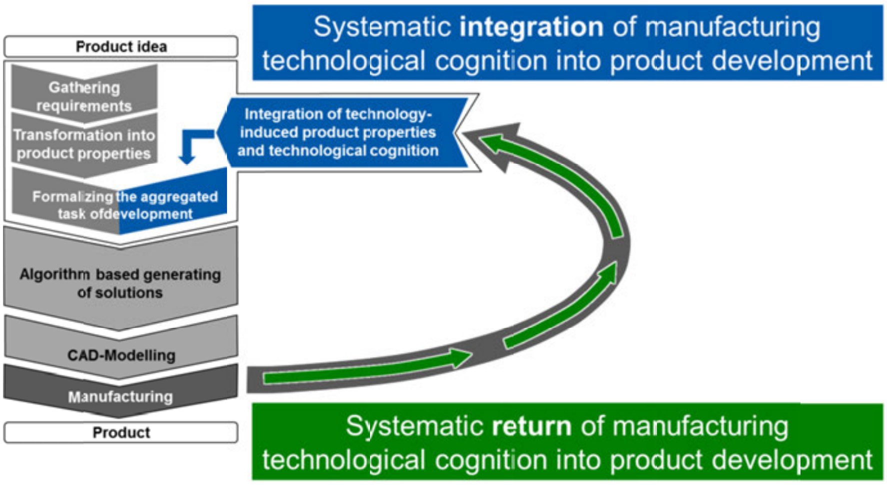


Figure 3. Steps of the approach

5.3 Formalizing manufacturing technological cognition

Manufacturing technological cognition can refer to several processes of the product life cycle, including manufacturing. Most of this cognition is very heterogeneous in the degree of formalization. In manufacturing technology linear flow splitting, great quantities of manufacturing technological cognition is found (Figure 4). This refers to different processes as well as to the manufactured products. The products are characterized by geometric information, for example, the linear flow splitted flanges and information on the material, like the ultra fine-grained microstructure [Groche et al. 2012]. Chambered profiles can be produced by further manufacturing steps, like roll forming [Doege and Behrens 2010].

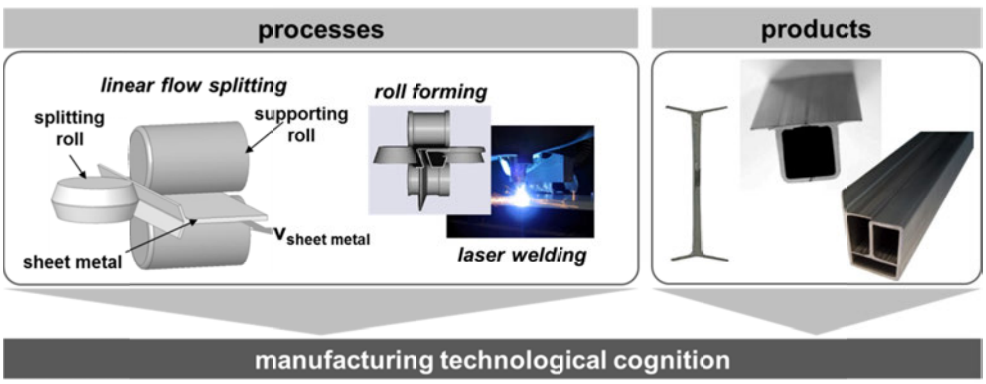
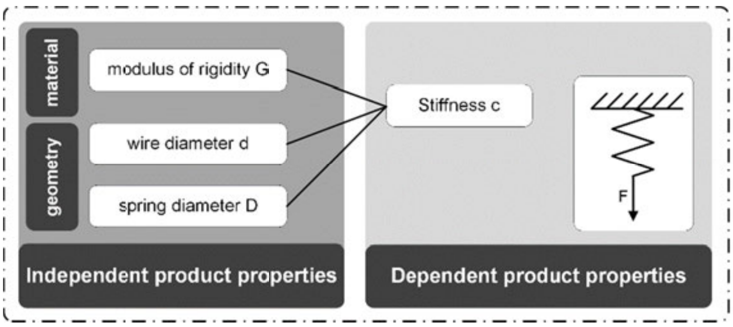


Figure 4. Sources of manufacturing technological cognition

For systematic return of manufacturing technological cognition, a uniform description is indispensable. Therefore, a formalization has to be defined. [Gramlich 2013] shows that using product properties is appropriate for the purpose of a formalized description. Thus, product properties are a means of documenting manufacturing technological cognition.
Manufacturing technological information can be allocated to the products which are used in processes as tools and as output of processes. Thus, this information can also be described by product properties. Product properties can be categorized into those which can be directly determined by the designer, the independent properties, and those that can only be influenced by determining the first described properties, the dependent properties [Birkhofer and Wäldele 2008].
Characteristics Properties Modelling (CPM) is another way of formalizing modeling of products, by differing between characteristics and properties, whereas a product designer is only able to determine the characteristics of a product [Weber 2005]. The properties of a product describe its behavior and cannot be influenced by a product designer. This classification is similar to the above-mentioned description. For all further discussions the description based on independent and dependent product properties is chosen.
Correlations between product properties are very important for describing manufacturing technological cognition. Only thus can links between information be found. One way to illustrate the correlations between product properties is to use product property networks [Wäldele 2012]. Property networks are graphical visualizations of the correlations between product properties. Figure 5 shows an example of a property network for a spring. It is especially meant for helical springs, which are exposed to torsion stress in the wire. The property network illustrates dependencies between material, geometry and stiffness in a spring. It highlights that the way in which the stiffness (c) of the spring depends on the independent properties (G, d_W, d_S) and could be influenced by the designer.
The statements regarding the correlations between product properties are also valid when considering processes, though the representation shown focuses on relations between product properties in terms of the function of the product.



$$c = \frac{Gd^4}{8nD^3}$$

n: number of active windings

Figure 5. Product property network of a spring

5.4 Extracting manufacturing technological information

The basis for each return of manufacturing technological cognition is examination of a manufacturing technology. This contains, for example, an analysis of manufacturing processes or examination of a product. The return of manufacturing technological cognition is split into two steps: gaining manufacturing technological information and linking the gathered information.
The first step is to clarify the gathering of information. The products and processes due to a manufacturing technology are screened by making experiments, simulations or analyses (Figure 6). The gathered information characterizes the functions of the products and their behavior in the processes of the product life cycle. The analyses are done by experts, for example, in the fields of manufacturing and materials science. It is important to document the information in a way that product designers can use them during product design. Therefore, the information has to be synchronized with the models used in the PD process. This could be ensured by formalizing information and describing them uniformly in terms of product properties.

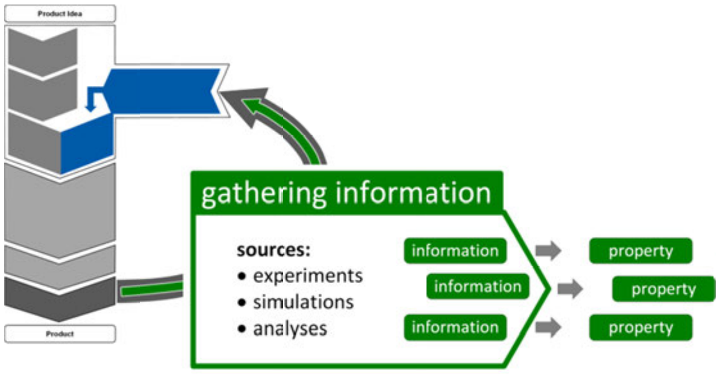


Figure 6. Gathering information as part of the return of manufacturing technological cognition

The manufacturing technology linear flow splitting provides sheet metal products with continuous flanges. These are characterized by special properties, like an ultra fine-grained microstructure and the specific geometry of the flanges. Information about the geometry or material, for example, the thickness of the flange or the anisotropy of the Young's modulus, can be gained by making measurements [Niehuesbernd et al. 2013]. Both are characteristic of the manufacturing technology, with a focus on the flanges (Figure7). As in [Gramlich 2013], the geometry and material properties are manufacturing-induced properties.

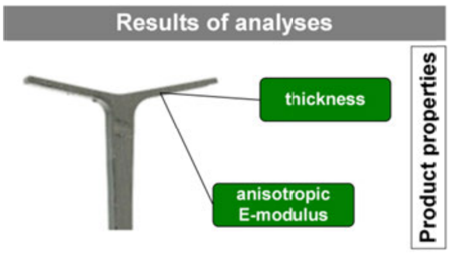


Figure 7. Gathered product properties

5.5 Gaining manufacturing technological cognition

Using only manufacturing technological information is insufficient when designing products. It is also important to know about correlations between information. Based on knowledge about the correlations it becomes clear at which stage of the PD process this information can be used. Based on already determined product properties during product design, the returned cognition on linkage reveal which manufacturing-induced properties also have to be considered. The linkage helps in understanding the correlations and using them for determining the product function during product design. Manufacturing technological cognition, as the linkage of information, has to be returned.

Manufacturing technological information is gathered from material examinations, for example. This information concerns the manufactured products. Thus, the information is documented as manufacturing-induced properties in a certain manufacturing technology. By planning and realizing examinations, several further properties of test parameters are also conducted. By interpreting the results of the examinations, an expert has to clarify how the test results correlate with the test parameters. Hence, the manufacturing-induced properties are already linked to further properties describing the test setup. Thus, the linkage describes correlations between manufacturing-induced properties and other product properties of the product function.

For the example of material examinations, different information and linkages can be gathered. Information on the Young's modulus can be linked to the used material, according to tests at linear flow split profiles. For ZStE500, an anisotropic Young's modulus with an increase of 30 GPa in longitudinal direction can be measured [Niehuesbernd et al. 2013]. This linkage between the material used and the anisotropy of the Young's modulus has to be prepared for integration into the PD process to tap the technological potential.

By interpreting the test results an expert also clarifies which linkage between the test results and the test parameters, including the properties of the tested product, is important (Figure 8). This is needed for the PD process to know how to influence the product function. Hence, this analysis of the importance of a linkage meets with the defined criteria for manufacturing technological cognition. Thus an expert has to ensure the importance or relevance of a linkage and its generality. Both are necessary criteria for cognition, without which cognition could not be used during the PD process.

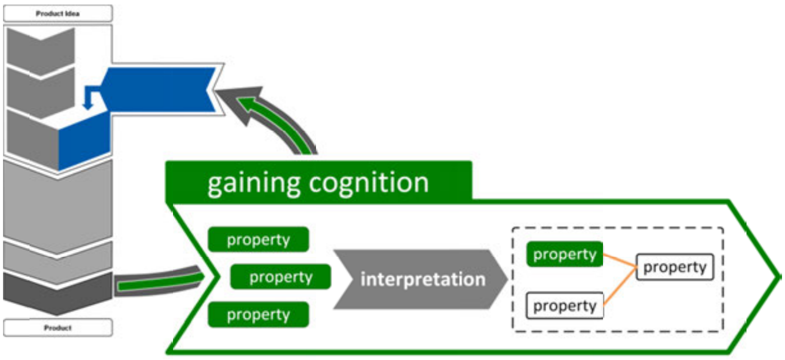


Figure 8. Gaining cognition as part of the return of cognition

The description by product properties can be used for modeling different correlations by modeling the links between the product properties. This comprises simple correlations, like for mechanical springs as showed in Figure 5, or complex correlations for a whole system. Therefore the mentioned property networks could be used.

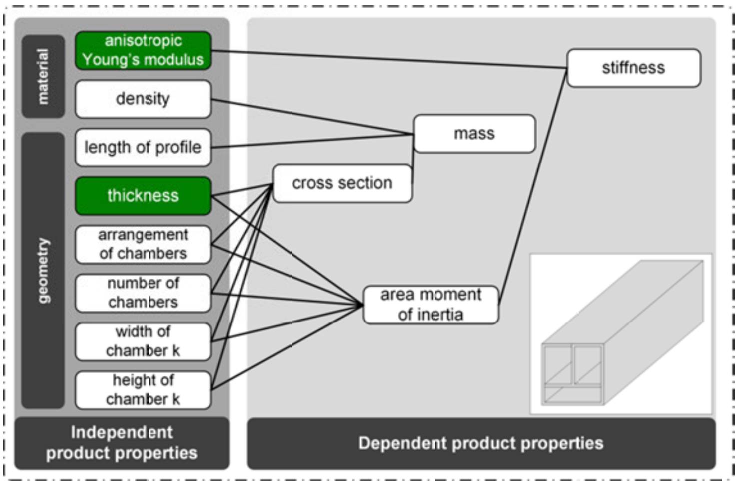


Figure 9. Property network with returned properties

An example of linked manufacturing technological information is a multi-chambered bending beam which is manufactured by linear flow splitting (Figure 9). The manufacturing-induced properties gained on the thickness of the flanges and the corresponding anisotropic Young's modulus are linked to several product properties. The stiffness of the bending beam is very important in fulfilling the product function. Therefore the manufacturing-induced product properties are identified as independent product properties in order to model the relevant correlations. The linkage of the manufacturing-induced properties to the other product properties is very important to understanding their influence on the stiffness and thus the product function of the bending beam. Manufacturing technological cognition is often used in the context of known correlations, as also shown in the example of the bending beam. The linkage of the area moment of inertia and the stiffness of the bending beam, for example, is basic knowledge of product designers. It can be used to better understand factors that influence stiffness of the bending beam. Thus, the gained manufacturing-

induced properties can be further linked to known linkage between product properties to understand how a manufacturing technology influences the entire product function.
After clarifying the impact of manufacturing-induced properties on the product function and then recording it as manufacturing technological cognition, the next step concentrates on using the linkages found to develop new products.

5.6 Options for the integration of manufacturing technological cognition

There are different ways to integrate cognition into the PD process (Figure 10). This especially corresponds with the degree of concretization of cognition.
The most formalized way of integrating cognition into the PD process is by using target functions and restrictions. Both can be used within an algorithm-based design approach. Therefore, the linkage between the product properties in the context of the product function has to be fully clarified. The advantage of this method of integration is that the influencers of a manufacturing technology can be considered early on in the PD process.
Another way to achieve integration is designing and using solution or design elements that apply manufacturing-induced properties specifically to fulfill the product function and to tap technological potentials. Thus, a product designer can adapt and integrate them easily during the product design process.
A further option for integration is to prepare design rules based on cognition of a manufacturing technology. These rules are mostly fairly general. Thus, they can be used at different points during the product design process. Design rules and solution elements are illustrated as examples in the following section.

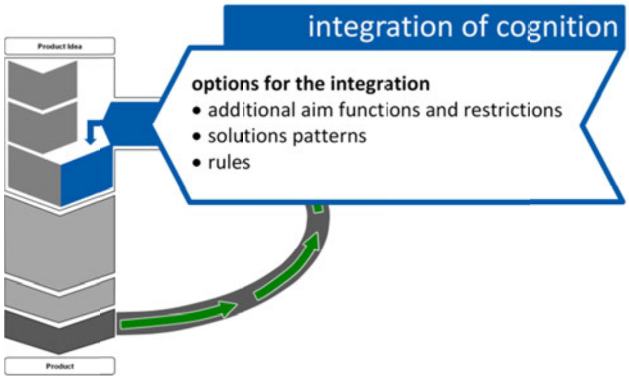


Figure 10. Integration of manufacturing technological cognition

The question of which point during PD can the formalized cognition be used depends on different aspects. As well as the degree of formalization, which properties are affected is also important. This could be, for example, geometric properties as well as properties which influence the active principles of a product.

6. Using the potential of a manufacturing technology by integrating cognition

The return of manufacturing technological cognition leads to the actual integration of cognition. As already shown, there are different ways to achieve integration. In addition to this, the most interesting aspect is how the returned manufacturing technological cognition influences the product design and the PD process. The following examples clarify and illustrate the advantages which arise out of the integration of manufacturing technological cognition. These examples are based on the manufacturing technology linear flow splitting in combination with the use of sheet metals as pre-product.
Linear flow split products are characterized by several manufacturing-induced properties. This concerns, for example, the anisotropy of the Young's modulus in the flanges [Niehuesbernd et al. 2013]. In longitudinal direction, the Young's modulus is higher than in the source material. Based on the return and integration, this manufacturing technological information can be used for designing a multi-chambered bending beam. Figure 11 shows a comparison between different arrangements of the

chamber walls inside the bending beam. Without considering the manufacturing-induced properties the stiffness of the bending beam is normalized to 100 %. When considering the anisotropic Young's modulus, how the linear flow split flanges are arranged as chamber walls is important. By varying the arrangement of the flanges, the stiffness of the bending beam can be improved by around 1 %. This percentage depends on the overall dimensions of the flanges as well as of the bending beam. Thus, the improvement could be significantly higher in a different scenario.
This improvement could be derived in a design rule for the arrangement of flanges in a linear flow split bending beam: The flanges should always be oriented in the direction of the external force in order to increase stiffness.

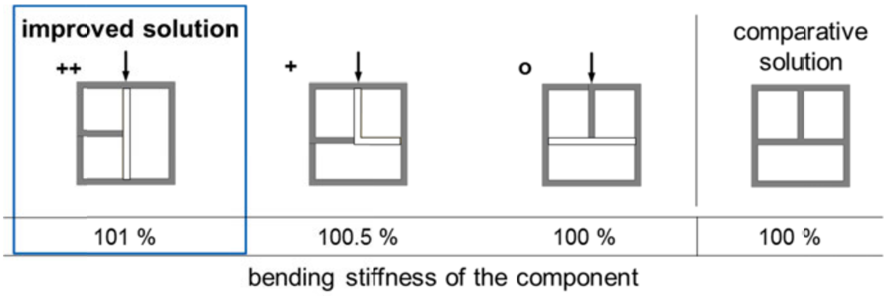


Figure 11. Using returned cognition in designing the cross section of a bending beam

Another example based on the manufacturing technology linear flow splitting concerns the great hardness of the surface at the flanges [Groche et al. 2012]. This could be used especially for the design of connections with a relative motion during assembling, for example, snap connections. Figure 12 shows different arrangements of splitting points, which leads to different positions of the upper flange surface. The different arrangements indicate that the best solution uses the upper flange surfaces as active surfaces for the snap connection. This leads to a higher number of assembling cycles because of reduced wear at the active surfaces. This cognition results in the following design rule: Use the flanges as active surfaces in order to increase the number of assembling cycles.

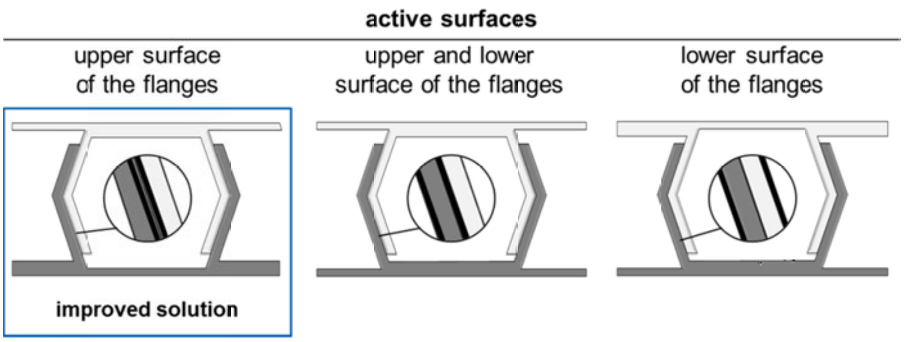


Figure 12. Using returned cognition in designing a snap connection

Deliberately simple examples were chosen to explain the facts and contexts of the approach developed for the return and integration of manufacturing technological cognition. This approach could also be used for more complex issues. The benefit generated could probably be proportionally higher.

7. Conclusion

The approach for systematically returning integrating manufacturing technological cognition allows the mastery of manufacturing technological influences of the product design process. The focus of this approach is on working out the potential of a manufacturing technology in product design. In contrast to previous approaches, it goes beyond ensuring the manufacturability of a product by considering manufacturing technology. The return and integration steps are built on the formalized description of cognition by product properties. This allows a uniform treatment of manufacturing technological cognition, regardless of where it came from. For the examples of a bending beam and a snap

connection it becomes clear that there are improvements when using this approach that go beyond ensuring manufacturability.
Based on this approach, classic product development procedures can be extended by systematically considering manufacturing technological influencers. The use of this approach for consistent algorithm-based design is also conceivable.

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Michael Roos, M.Sc., Research Associate
Technische Universität Darmstadt, Institute for Product Development and Machine Elements
Magdalenenstraße 4, 64289 Darmstadt, Germany
Telephone: +49 (0)6151-16 25 55
Telefax: +49 (0)6151-16 33 55
Email: roos@pmd.tu-darmstadt.de
URL: http://www.pmd.tu-darmstadt.de