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PROVIDING PROPERTIES FOR THE OPTIMIZATION OF BRANCHED SHEET METAL PRODUCTS

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ABSTRACT

This paper presents an approach for designing profile structures made by a new manufacturing process, called linear flow splitting. The approach distinguishes between internal and external properties. Properties which can be directly defined by the designer, such as geometrical properties, are called internal properties. The internal properties define the desired properties of the product, which can be observed by the user, the external properties.
This new approach for providing and structuring properties is used for optimization processes pertaining to this new manufacturing process for profile structures. Therefore product properties are analyzed and categorized into internal and external properties, in so called property-networks. These networks visualize the interrelationship between internal and external properties. Not only can those structured properties be used by downstream mathematical optimization processes, but the designer can also develop a feeling for the dependencies of properties and the influence of property changes to meet certain required external properties.
To ensure the manufacturability of the part and reduce the number of iterations made in conventional product development, the technological findings coming from production and evaluation should be made accessible in the product development process. The manufacturing process influences the internal properties of the product by introducing new product properties and restrictions.

Keywords: algorithm-based design, external properties, internal properties, optimization, sheet metal, technological findings

1 INTRODUCTION

Linear flow splitting allows branched profiles to be formed using sheet metal in integral style without joining, laminating material or heating the semi-finished part. Using a subsequent forming process, new multi-chambered structures with thin-walled cross-sections can be made from sheet metal.
Since this forming technique is at an early stage of development, a way to integrate it into the product design process must be developed. Therefore, the goal of the Collaborative Research Center 666 (Sonderforschungsbereich 666), which was founded in 2005, is to exemplify how branched sheet metal products can be designed and how a manufacturing process can be integrated into the design process. The main emphasis of this contribution is placed on the first partial project of the CRC 666, the transformation from customer requirements and market requirements into product properties. To design these products, one has to consider the large amount of market influence on feasible product geometries and materials. To do this, one has to know how product properties influence the requirements of the product. A product is built because certain properties are desired and used [1]. The distinction between the observable and desired properties of a product (external properties), and the constructive parameters the designer chooses to define to obtain the desired properties (internal properties) is one fundamental aspect of this new approach. An external property does not come into being on its own, it is always the result of the product's internal properties, and vice versa. Every change made to an internal property has a direct effect on an external property, or in most cases, a whole set of external properties.
Consequently, the realized product always has both internal and external properties. This necessitates good knowledge of both those properties to be established by designing and optimizing (internal properties) and the properties desired for the product (external properties) [1].

The intention of the CRC 666 is to provide a foundation of new methods and techniques for achieving optimized representations of higher order bifurcations in integrated sheet metal design. To ensure the manufacturability of the algorithm based product, the development needs technological findings from the production and evaluation. The manufacturing limits of the linear flow splitting tooling system and new product properties induced in the fully-machined profile structures complement the input of the mathematical optimization.

2 INTEGRAL PROFILE STRUCTURES MADE BY FORMING PROCESSES

2.1 Principle of Forming Processes

In nature, branched structures are used for numerous purposes, e.g. to provide stability in a leaf. So far, branched sheet metal structures were mainly produced in differential style, i.e. by gluing, welding or similar procedures or by material sheeting. These procedures have several disadvantages: they are heavier, have lower thermal conductivity, a higher disposition to corrosion and are more likely to break due to instability at the connecting piece or the double layer. To avoid these disadvantages, the new technique of linear flow splitting [2] can be applied. It is a new massive forming process for the production of bifurcated profiles in integral style. The semi-finished part is a sheet metal plane, which is transformed at ambient temperature by a specific tooling system consisting of obtuse angled splitting rolls and supporting rolls. The fixed tool system forms the translatory moved work piece in several steps up to a profile with the final geometry. The further processing of the split sheet metal by roll forming and bending procedures presents the opportunity to produce profiles with new cross-sections from sheet metal. Using renewed linear flow splitting of the end of the flange and forming of the profiles, numerous new possibilities for chambered profiles optimizing lightweight design arise [3]. In comparison with the bar extrusion process, e.g., the continued processing of linear flow split profiles offers the possibility to integrate features into the profile using milling or drilling procedures, for example. Figure 1 shows such a profile with one free flange and three chambers with integrated bore holes at the inside of the chamber. To produce those multi-chambered profiles, a continuous production line is established. It consists of several linear flow splitting tool systems and roll forming tool systems in one production line.

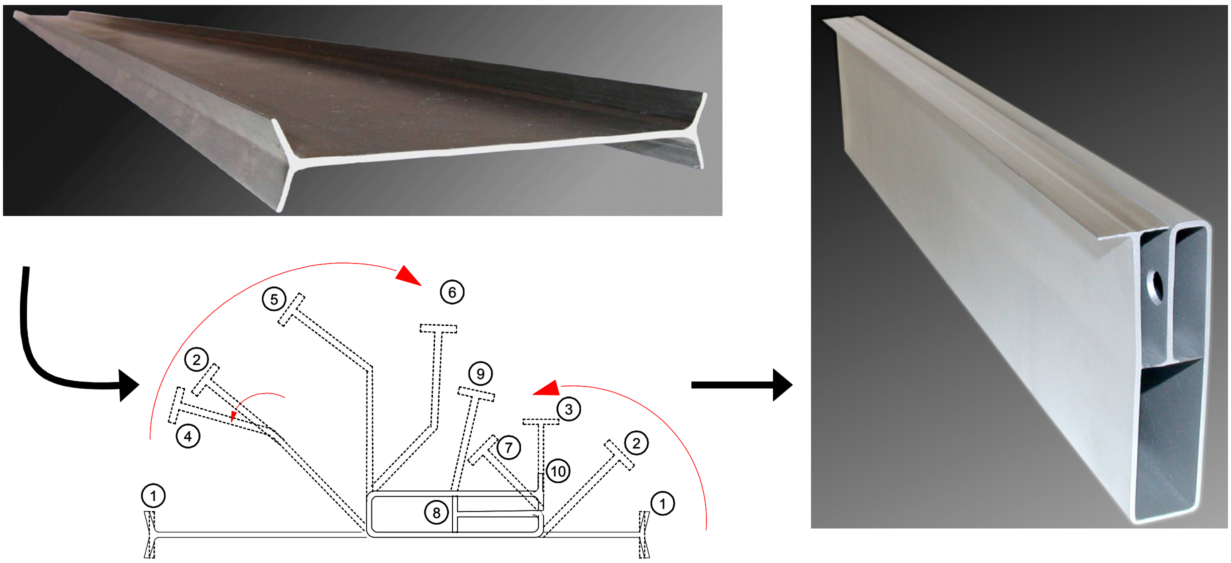

Figure 1. Manufacturing a 3-chambered Profile

At the present time, the stabilizing branches in the wings of airplanes are milled out of huge blocks of material. Stringer constructions in the shipbuilding industry are welded onto the material, which is time consuming and leads to a change in the microstructure of the welding joint. Manufacturing those parts with integral style branches by using linear flow splitting could eliminate these drawbacks.

3 PRODUCT DESIGN: AN OPTIMIZATION OF INTERNAL PROPERTIES

Product design is a process of variation and selection over different phases, by adding product properties with every step and becoming more and more concrete [4]. The general design process starts with the definition of user needs and desires, also called user requirements [5] that are partly specified in the non-technical vocabulary of the users. They describe what the system should do and not how the solution should be implemented. The work result should be a requirement list. It comprises requirements which a product should fulfill. Designers have the task of meeting these requirements using the product's outward properties, called external properties. An external property never exists in itself, it is always the result of internal properties. They must be realized by the exact determination of internal properties. This means designers must choose internal properties in such a way that the required external properties are met as closely as possible. As shown in Figure 2, a profile has certain internal and resulting external properties.

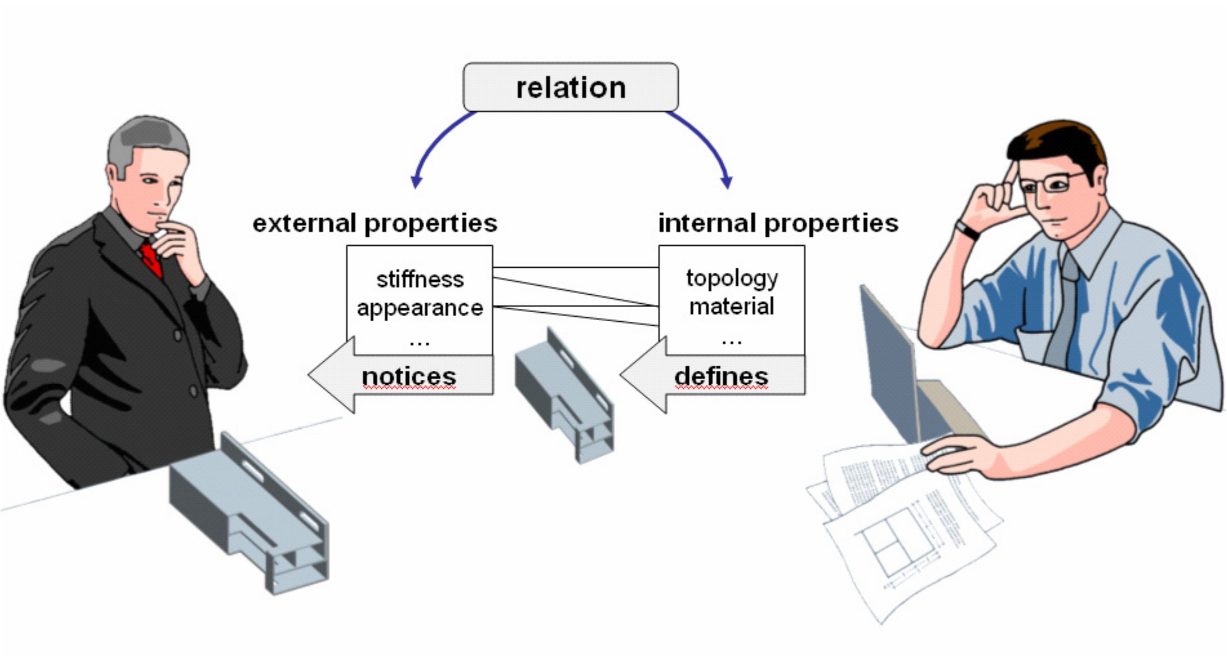

Figure 2. Optimization of Internal Properties to Achieve External Properties

Engineering design is based on the interplay between "what we want to achieve" and "how we choose to satisfy the need" [6]. A designer asks: what shall I add or change in my sketch, drawing, or product model in order to meet the requirements? The question could also be: which internal properties, such as geometry or material, shall I choose or change in consideration of the given requirements representing customer and market needs? [7] The difficulty for a designer is to create and optimize the desired external properties using internal properties. Everything which is changed in a technical drawing, e.g. geometric data, certain features or the material – all internal properties – has a direct effect on the external properties perceived by a customer. Therefore, the knowledge of the connection and interplay between the internal properties and external properties is the basis for a good design and a prerequisite for a successful designer.

The link between internal and external properties is often given by models like the beam deflection model or general mechanic formulas. It links, for example, the deflection of a beam to the load, as well as to the geometrical and material properties of the beam itself. This specific design knowledge enables one to decide what needs to be done in order to meet the requirements. Apart from the linear flow splitting example, the concept of internal and external properties may prove as a basis for structuring design knowledge in general. Properties are linked to each other and create a property-network [7]. Currently, the transformation of the customer wishes and requirements into product properties depends on the know-how and the intuition of the engineer. A major challenge, therefore, is the successful realization of such a property-network, in which properties are related to each other. Truly, one has to admit that such a network could hardly be developed for universal applications. The call to generate a complete and general list of all properties is old, but not easily satisfied. [1] Some attempts to assemble such a list are known, e.g. VDI 2225 in dependence of Kesselring [8], but they have not been successful. To create the interrelations of those properties is even harder, so it seems more realistic to expect a domain-, branch- or even product-specific property-network, e.g. a property-network for designing linear flow split profiles. One main focus of this approach is to elaborate the customer and market requirements just for the specific branch of profile structures in such a way that a mathematical optimization process can follow.

3.1 Dependencies of Internal and External Properties

To represent the dependencies of properties and each property chain, coming from external to internal property, a network structure (Figure 3) is introduced. In this network structure, called the property-network, the dependencies are clearly defined. The nodes of the network structure represent the properties (e.g. P_{11}). The lines, also called edges, show the interrelationship between each property (e.g. P_1 to P_{11}) with the relation (e.g. r_2) amongst them.

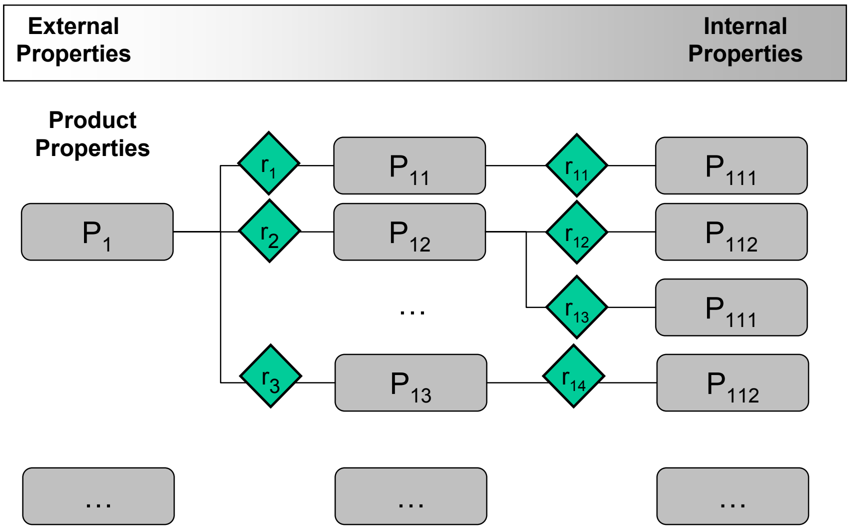

Figure 3. Dependencies of Properties

As was already mentioned, external properties can always be traced backed to internal properties. This means that internal and external properties always have a certain relationship to one another. Not only must the designer know which individual parameters create an external property, he must also know which constructive parameters, and therefore internal properties, he must adjust to achieve his desired external properties.

In the early phases of design, the formal, physical connections play a particular role. External properties can be linked to the internal properties using a mathematical, formal relation. For instance, consider the example of a cable conduit's deflection. We already established that the profile's deflection, as an external property, is a result of a number of internal properties.

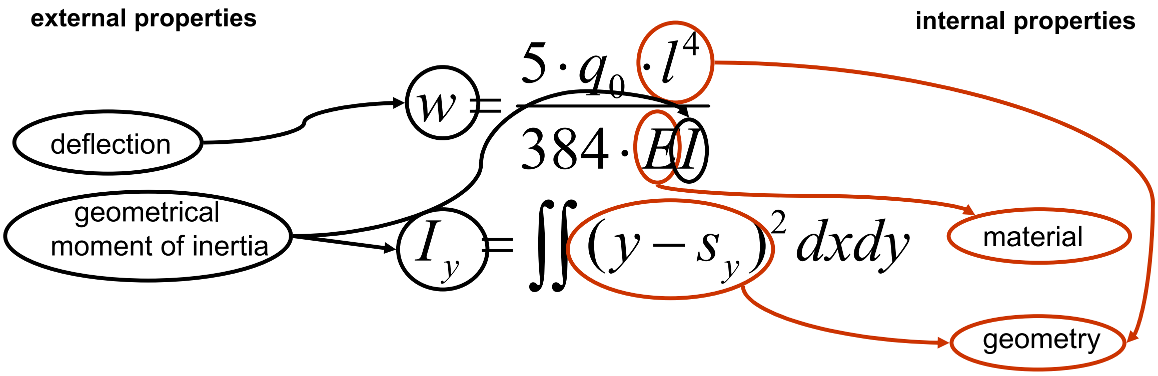

Figure 4. External and Internal Properties

However, we have not yet mentioned the relationship between these parameters. If the designer wants to minimize the deflection, not only must he know which internal properties to change, but also how he should change these parameters in order to achieve increased flexural strength and therefore lower deflection. This example makes it clear that in order to minimize the deflection, the geometry must be changed or the modulus of elasticity must be increased. The designer can systematically change one or more internal properties in order to arrive at the desired deflection.

It is also important to note that when optimizing the deflection, the modulus of elasticity cannot be changed arbitrarily. The modulus of elasticity is always a result of the selected material and is a set material parameter. This means that there is a discretely assigned value for every material. However, it becomes more complicated when there are no longer clear, formal connections between the properties. The designer must understand even these heuristic connections – connections without a clear, mathematical connection.

For instance, good haptics of an example product is required as a specification, and therefore an external property. There is no doubt that good haptics depend on the outer design of the product, among other things, and can be traced back to the internal properties of the shape and finally the geometry, the material and the surface. A simplified network of relations between the external properties and internal properties can be developed. However, the clear connections, like which internal properties need adjustment, are missing. Due to the complexity of these heuristic connections, emphasis is first placed on the formal relations between internal and external properties when developing models.

Each chain represents a new alternative to change internal properties to meet the customer demands. A necessary prerequisite is the existence of such a network structure. It has to be established from different analysis steps from known physical models, tables, diagrams or even experimental knowledge based on empirical data.

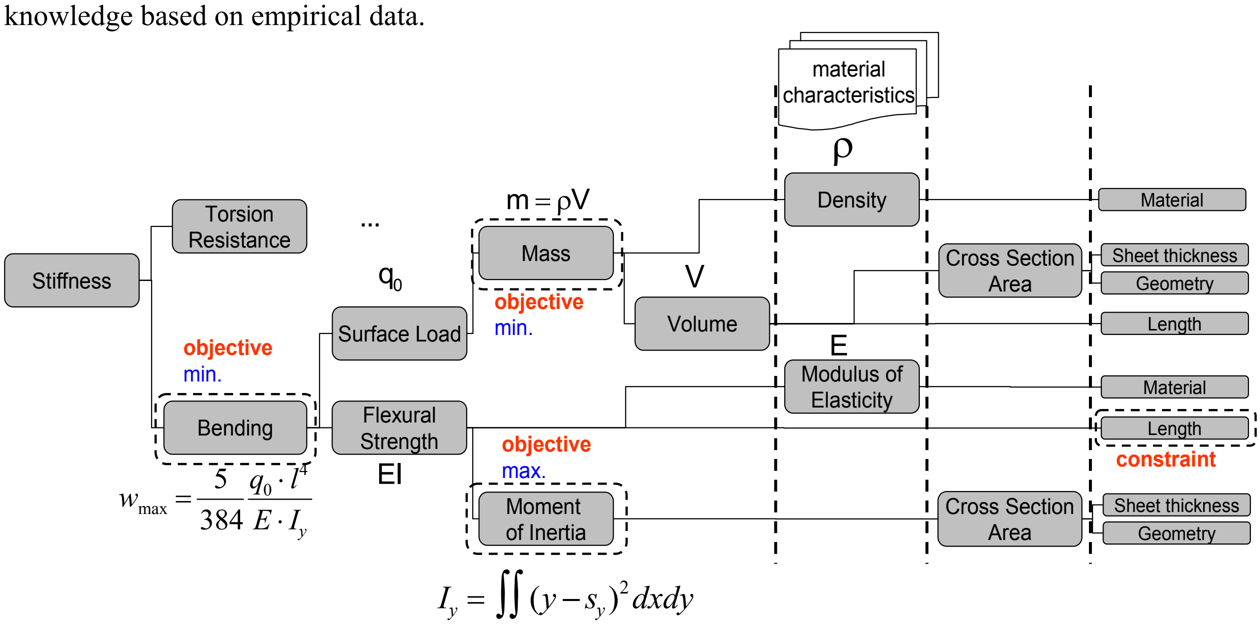

Figure 5. Property-Network

Exemplarily this formula of the deflection of a beam was implemented into a property-network structure (Figure 5). As one can see, the clear and precise interrelationships between different kinds of properties come out. The property chains coming from the desired external property "stiffness" to internal properties such as geometry show precisely how properties interact.

Another major advantage of such a network is the distinct transformation of wanted, unwanted and limiting product properties. These properties are characterized as objectives, the wanted properties, we are looking for and the constraints, unwanted properties and limiting values to our optimization problem. Constraints and objectives are tagged in the property-network and will show the right direction for the following optimization process.

3.2 Constraints and Objectives

As was previously mentioned it is important and a prerequisite for subsequent optimization processes that constraints and objectives of the design task are well formulated. The difference between objectives and constraints is that objectives are usually stated as "wanted" properties that a design should have in order to be an acceptable and good solution [9], such as “the profile should not bend,” while constraints are values to certain product properties which indicate limitations on possible design solutions. The constraints play an extremely important role in the design process, especially in the initial phases, when the preliminary design is made [10]. They limit the solution space and therefore the scope for the optimization of solution variants. For example, a constraint might specify that the weight of profile structures should be less than 40 kg, limit the value of the installation space or the number of chambers inside of our profile. Every solution with a different value of a certain property is a non-solution which is not feasible and therefore of no interest for further optimization, e.g. of the topology of a profile structure. Objectives are derived from the requirements a product should have. An objective is a certain property that should be optimized such as “the profile should be lightweight” or “the profile should not bend too much”.

3.3 Optimization Using this Approach

These formalized interrelationships are used by downstream mathematical optimization processes to compute new geometries and to evaluate them to find the best solution. A case study of a cable conduit was carried out to obtain insight into the feasibility of a computer-based algorithmization of the early phases of design, which is usually described as the most appropriate domain of human problem-solving.

Solving this task means transforming a verbal product representation into a graphical one, which comprises all product properties needed for manufacturing. Regarding the low deflection of a beam structure, the interrelation of requirements and design parameters can be modeled by physical effects and be expressed in terms of equations. The case study “cable conduit” uses this concept of structuring and linking properties with each other to settle equations, which relate deflection to the length and cross-section of the conduit’s profile. These equations can often be non-linear, such as elasticity or heat transfer, and make the corresponding mathematical model most complex and highly difficult to solve [11]. To find feasible solutions very quickly, the mathematical optimization process is broken down into two stages.

In stage one, a coarse mixed-integer programming (MIP) model, like pre-processing, primal-heuristics, dual algorithms or branch-and-cut algorithms, was solved with linearized functional relations to find the overall topology of the product [11]. The cross section is discretized by a rectangular pixel grid. The channels cannot be placed and shaped freely within the cross section; they have to obey the pixels. That means, the pixels carry the information to which channel they belong (if any). A complete assignment of all channels to pixels is called the design or topology of the conduit. Sheet metal is then wrapped around the channels, such that they are separated from both the other channels and from the outside [11].

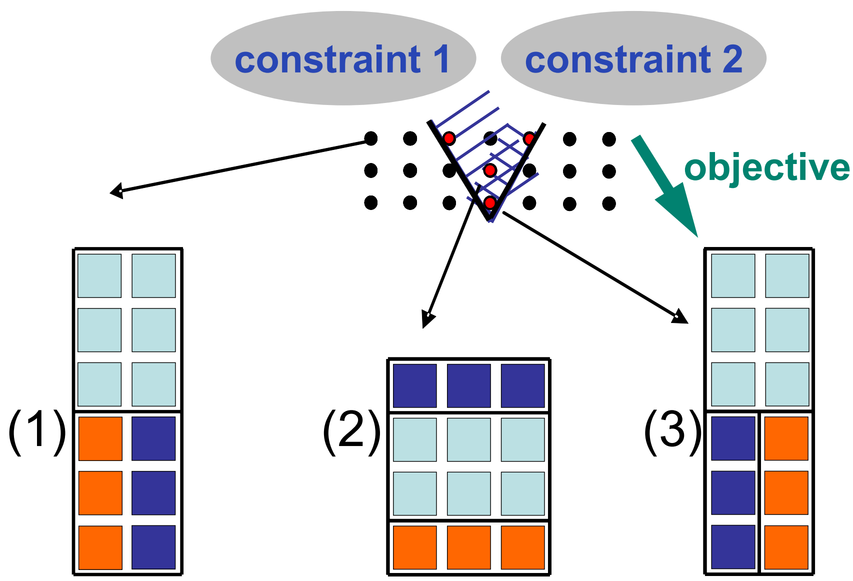

Figure 6. Generating feasible and Non-Feasible Solutions

One can now generate all pixel arrangements which fulfil the constraints (Figure 6), e.g. having 3 separated channels. These pixel arrangements were evaluated and ranked with regard to objectives and wishes, e.g. low deflection and small torsional.

Once again, a well-defined methodical basis proves a major advantage for the computerization of such a design process:

- Constraints include feasible (Figure 6, numbers (2) and (3)) and exclude non-feasible solutions (Figure 6, number (1)) in the entire solution area.
- Objectives and wishes allow one to rank the remaining solutions in regard to their performance.

Our ongoing research concentrates on an inclusion of further engineering constraints, such as heat transfer or fluid mechanics. It is easy to see that the optimized topology includes desired properties and corresponds well to the rules of beam bending. To get a low deflection of the profile, it is necessary to have as much material as far from the bending axis as possible.

In stage two, a more detailed product geometry should be obtained by solving a non-linear continuous shape optimization model. Technological findings will also be considered. Given a profile with functionally optimized product geometry, it must still be determined how it can be manufactured using a linear flow splitting process. Every branch in the profile can be obtained by either splitting up the piece of sheet metal or by connecting two branches together. Because there are normally many ways to design one cross-section, an algorithm-based approach must decide where to cut and where to connect. Once again, it must be mentioned here that all distinctive algorithms are used simultaneously to create an optimal solution in terms of functionality and producibility and to avoid dead ends in the design process. The case study was carried out to obtain insight into the feasibility of computer-based algorithmization of the early phases of design.

4 INTEGRATION OF TECHNOLOGICAL FINDINGS

The property networks represent the relations between the external and internal properties, starting from the requirements of the customers. These relations are created predominantly by existing knowledge provided by scientific literature. The systematic studies of the newly developed forming process, linear flow splitting, generate a lot of scientific findings not previously considered in scientific literature and therefore not yet considered in the property network. Besides the optimization of sheet metal products according to market-driven internal and external properties, technological findings from the production process and the evaluation, such as structural and materials testing also have a great influence on sheet metal products and their properties. In conventional product development, these technological findings from the downstream production line are regarded mostly as time-consuming and iterative improvements. The minimization of the number of iterations and the required expenditure, as well as the support of the mathematical optimization of the product development process, are the intentions of the future work. An important aspect of taking technological findings into account is, on the one hand, the identification of manufacturing limits [12] of the linear flow splitting tooling system and, on the other hand, to utilize new properties induced in the bifurcated profile e.g. increased micro hardness, higher stiffness and low surface roughness.

4.1 Why consider Technological Findings?

The development and optimization of a product based only on the required external properties can lead to dead ends, due to the negligence of manufacturing restrictions in the design process. In this way, it is not ensured that the product, in our case a profile in integral style, is manufacturable. Design elements that pose manufacturability problems can be e. g. a thin cross-section between two chambers of a profile to realize a good heat exchange. The linear flow splitting machine can only produce bifurcations with flange widths within certain limits. At the moment the minimal realized flange thickness is approx. 1mm. This value cannot be under-run if the mentioned cross-section is composed of a flange. Thus it appears that the shape of the profile must subsequently be changed. To avoid this time-consuming iteration it is indispensable to take manufacturing restrictions into account and to integrate them into the algorithm based design process.

The identification of those manufacturing restrictions is based on an analysis of the technological findings of the production line provided by the evaluation of the semi-finished parts, the produced bifurcated profiles and the manufacturing process. This analysis leads to a set of new product properties of the profiles, e.g. the very low surface roughness at the upper side of the flange or an increased micro hardness caused by strain hardening in the contact area of the splitting roll radius [3].

4.2 Influence of the Manufacturing Process on the Product

To determine the influence of the technological findings on the product properties, it is reasonable to regard the life-cycle of a profile manufactured in an integral style. The profile passes through the four phases, production of material, product manufacturing, uses and recycling or disposal. Each phase of the life-cycle chain starting from the production of the material affects the product properties.

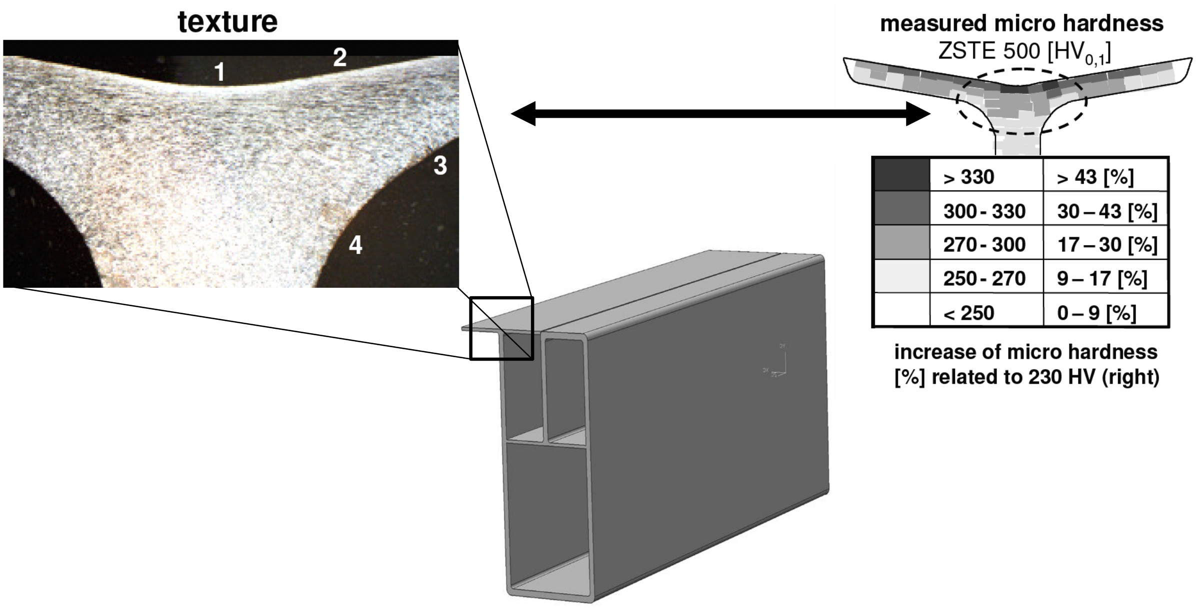

Figure 7: Distribution of the Micro Hardness in the Bifurcated Profile

The production of material defines and changes the material properties like hardness, modulus of elasticity, toughness. Product properties, e.g. material properties as internal properties, are changed. The identification of those properties is based on an analysis of the technological findings of the production line provided by the evaluation of the semi-finished parts, the produced bifurcated profiles and the manufacturing process. Those findings are used to refine the relations of properties during the product development process.

The micro hardness increases up to 40% on the upper side of the flanges of a bifurcation (Figure 7) [3], whereas the distribution of the hardness of the web remains nearly the same as in the sheet metal. This fact enables the mathematical optimization of the algorithm-based product development to locate the upper side of the flanges in areas of the profile exposed to abrasion, like the surface of linear guides.

The change of the surface properties during manufacturing shows an interaction of the linear flow splitting process and the external and internal product properties.

For instance the external property of a "shiny surface" can be realized by the internal property of extremely low surface roughness, due to the linear flow splitting process and the geometric information "upper side of the profile" as the input for the mathematical optimization.

5 SUMMARY AND CONCLUSION

In this contribution, examples have shown that the knowledge of properties is of fundamental importance. All technical products are built because certain properties are required.

Future work on an algorithm-based design, and therefore ongoing work in the CRC 666, will consist, on the one hand, of a more elaborate description of properties and their relationships to each other in the form of an investigation of more physical models, tables, diagrams, etc. An entire collection of rules is the basis for further optimization processes. On the other hand, the data and information of these relationships will be depicted in formulas, if-then rules, semantic networks, and so on. Additional research must be done.

One of the primary tasks will be to detect the influence of technological findings from downstream production lines (branches of production subsequent to product development). Regarding the variation of the representation of the information (protocols, diagrams, series of measurements etc.), these findings will be standardized. They will be edited and provided to the mathematical optimization of the development process as constructive design parameters, just like the internal properties interacting with external properties. It also presents a starting point for considering technological findings in the algorithm-based product design. An important aspect concerning the mathematical optimization is that the restrictions set by the manufacturing process are accompanied by new product properties. A further issue in the future will be to complete the analysis of the influence of all product properties induced by the manufacturing process on the external properties.
Apart from the linear flow splitting-example, the concept of internal and external properties may prove as a basis for structuring design knowledge in general. However, it remains a great challenge to grasp those relationships, which are not yet fixed or known, e.g. internal properties that represent good styling.

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REFERENCES

[1] Hubka, V., Eder, E., "Design Science", Springer Berlin Germany, 1996.
[2] Jöckel, M., "Grundlagen des Spaltprofilierens von Blechplatinen", Berichte aus Produktion und Umformtechnik, PhD Thesis TU Darmstadt, Shaker Aachen Germany, 2005.
[3] Groche, P., Vucic, D, "Multi-chambered profiles made from high-strength sheets", Production Engineering, Annals of the WGP, Vol. XIII/1, Hannover Germany, 2006.
[4] VDI-Guideline 2221, "Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte", Beuth-Verlag Düsseldorf Germany, 1993.
[5] Stevens, R., Brook, P., Jackson, K., Arnold, S. "Systems Engineering: Coping with Complexity" Prentice Hall PTR, 1998.
[6] Suh, N. P., "Axiomatic Design as a Basis for Universal Design Theory", Shaker Aachen Germany, 1998.
[7] Wäldele, M., Vucic, D., Birkhofer, H., "A new manufacturing process as the seed for an algorithm-based product design in the early phases", NordDesign2006, Reykjavik Iceland, 2006.
[8] Kesselring, F., "Bewertung von Konstruktionen." Deutscher Ingenieur Verlag GmbH, Düsseldorf. 1951.
[9] Wielinga, B. J., Akkermans, H., and Schreiber, G. "A formal analysis of parametric design" In Gaines, B. R. and Musen, M. A., editors, Proceedings of the 9th Banff Knowledge Acquisition for Knowledge-Based Systems Workshop, Alberta Canada, 1995.
[10] Leemhuis, H., „Funktionsgetriebene Konstruktion als Grundlage verbesserter Produktentwicklung", PhD Thesis, TU Berlin Germany, 2004.
[11] Birkhofer, H., Martin, A., Ulbrich, S., Wäldele, M., Fügenschuh, A., Günther, U., Junglas, D., Sauer, T., Walter, S., "Topology- and shape-optimization of branched sheet metal products". In print in: H. Kopfer (Ed.), Operations Research Proceedings, Springer Berlin Germany, 2005.
[12] Delbressine, F.L.M., Hijink, J.A.W., "Discrete Part Design by Taking Manufacturing Restrictions into Account" CIRP Annals, Vol. 40'/1/1991, Manufacturing Technology, Hallwag Ltd. Bern, 1991.

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