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A new manufacturing process as the seed for an algorithm-based product design in the early phases

M. Wäldele

Technische Universität Darmstadt
Product Development and Machine Elements
Magdalenenstraße 4
64289 Darmstadt
Germany
waeldele@pmd.tu-darmstadt.de

D. Vucic

Technische Universität Darmstadt
Production Engineering and Forming Machines
Petersenstraße 30
64287 Darmstadt
Germany
vucic@ptu.tu-darmstadt.de

H. Birkhofer

Technische Universität Darmstadt
Product Development and Machine Elements
Magdalenenstraße 4
64289 Darmstadt
Germany
birkhofer@pmd.tu-darmstadt.de

Abstract

This paper presents an approach to designing profile structures made by a new manufacturing process called linear flow splitting. New geometries can be manufactured in integral style out of the semi-finished product sheet metal.

For those profile structures, product properties are analyzed and structured in a so-called property-network, which visualizes the interrelationship between different product properties. This will give the designer a feeling for the dependencies of properties and the influence of property changes to meet required demands.

A well structured property-network could also be a first step towards an algorithm-based product design and makes parameters for downstream mathematical optimization process accessible. This first approach of structuring properties is demonstrated by a case study of the design of a poster stand and is also used in a mathematical optimization of a profile structure to deflect the length.

Keywords: Algorithm-based design, design science, optimization, product properties, property-network, sheet metal

1 Introduction

Sheet metal is one of the most commonly used semi-finished products in metalworking. Countless everyday products are made from it. Its main characteristic is the ability to be formed and shaped up to high deformation degrees. Linear flow splitting enables the forming of branched profiles in integral style made of sheet metal without the joining, lamination of material or heating of the semi-finished part. By a subsequent forming process, new multi-chambered structures with thin-walled cross-sections can be made from sheet metal.

As this forming technique is at an early stage of development, a way to integrate it into the product design process has to be developed. Therefore, the aim of the Collaborative Research

Center 666 (Sonderforschungsbereich 666), which was founded 2005, is to exemplify how branched sheet metal products can be designed and how a manufacturing process can be integrated into the design process. To design these products one has to consider the huge amount of market influences on feasible product geometries and materials. To do this, one has to know how product properties influence the requirements of the product. The intention of CRC 666 is to provide the fundamentals of new methods and techniques for gaining optimized representations of higher order bifurcations in integrated sheet metal design.

The creation of entirely new methods in the development and production process of multifunctional products is the aim of this research program. The research activities cover the product creation in a holistic sense. Starting with the definition of the requested specifications, they also include product design, manufacturing and product evaluation, as well as virtual product development. Engineers, mathematicians and material scientists are involved in the research center. Thus, synergetic effects as well as problem formulations and research hypotheses due to the resulting interfaces between the different disciplines are expected [1].

The knowledge of properties and their relationship to each other is the basis for a computer-based creation of topology and geometry out of formalized verbal requirements without requiring at least a rough geometrical concept created by humans [2]. In the last decades, a vast amount of knowledge, methods and tools has been elaborated upon by design researchers and considerable effort has been invested in theories and models of technical products.

2 Linear Flow Splitting – Profile Structures in Integral Style

Principle of Linear Flow Splitting

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 the instability at the connecting piece or the double layer. To avoid these disadvantages, the new technique of linear flow splitting [3] 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 discreet steps up to a profile with the final geometry.

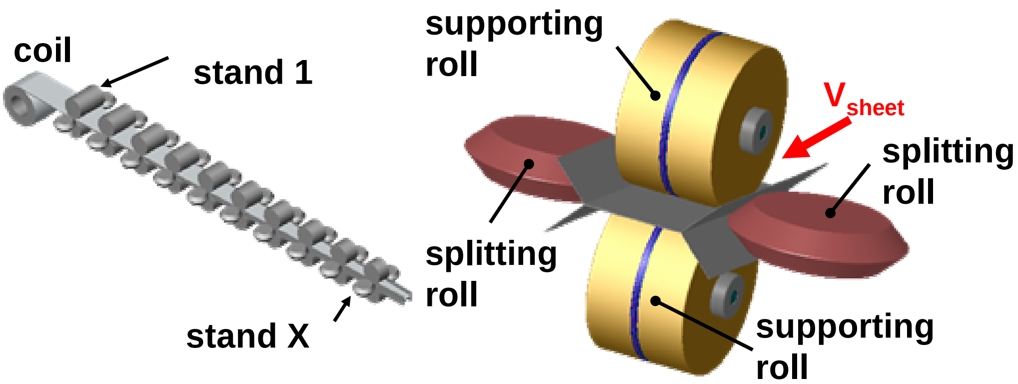

Figure 1. Linear Flow Splitting

The bifurcations originate from a surface enlargement of the sheet metal's band edge during material forming. Induced high hydrostatic compressive stresses in the local forming zone during the process lead to an increased formability of the material and thereby to the realization of large strains. The bifurcated profile is marked by a bar and two flanges. The surface beneath the splitting roll is defined as the upper side.
The realization of a continuous production line offers the opportunity for high output per unit of time, whereas the dimension tolerance could be minimized as seen, for instance, at the roll forming technology [4]. Several of the linear flow splitting tool systems could be arranged consecutively to reach the desired splitting depth in increments (figure 1, left). The sum of each incremental step is the desired splitting depth of the produced part. Moreover, two diametrically positioned splitting rolls offer the opportunity to produce double-sided bifurcated profiles (figure1, right). The supporting rolls cover the whole sheet metal to avoid buckling of the plates.

Geometries made by Linear Flow Splitting and Roll Forming
The further processing of the split sheet metal by roll forming and bending procedures offers the opportunity to produce profiles with new cross-sections from sheet metal. By renewed linear flow splitting of the end of the flange and/or forming of the profiles, numerous new possibilities of chambered profiles optimizing lightweight design arise [5]. In comparison to the bar extrusion process, e.g., the continued processing of linear flow split profiles offers the possibility to integrate features in the profile using milling or drilling procedures, for example. For demonstration purposes, a profile with one free flange and three chambers was welded with integrated bores (figure 2). In the next step, multi-chambered profiles will be manufactured in a continuous production line with thin-walled cross-sections from high-strength sheets by roll forming linear flow split profiles.

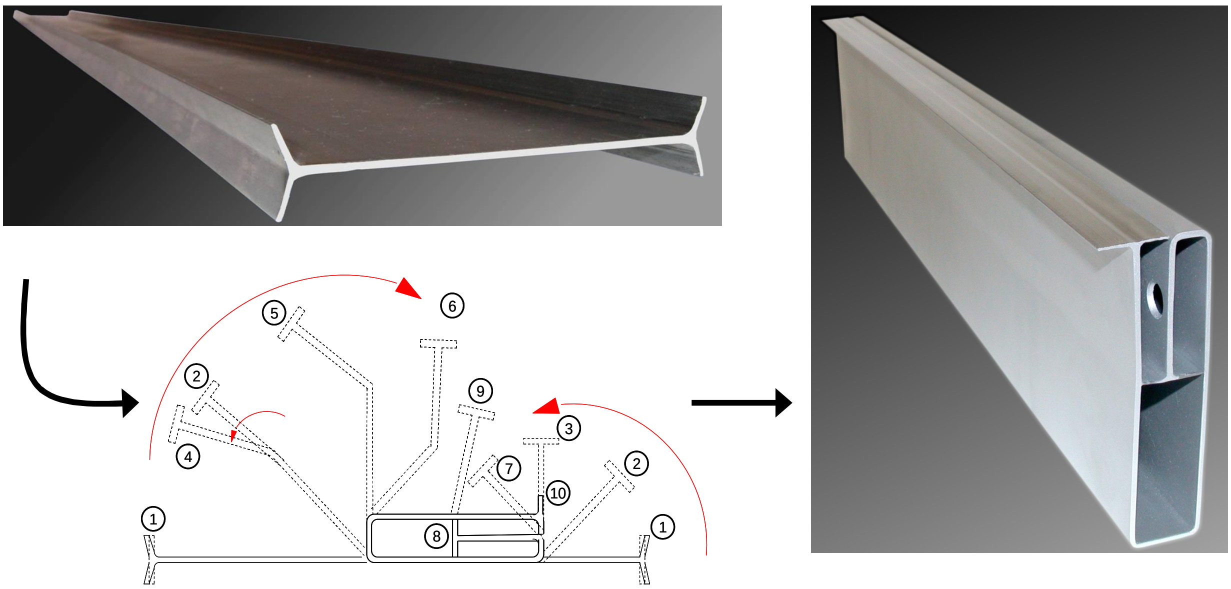

Figure 2. Manufacturing of a 3-Chambered Profile Structure

These profile structures have many advantages and offer new perspectives to different industries to improve their products. At present time, the stabilization branches in the wings of airplanes are milled out of huge blocks of material; stringer constructions in the shipbuilding industry are welded on the material, which is time consuming and leads to a change of microstructure in the welding joint. Manufacturing those parts with integral style branches by using linear flow splitting could eliminate these disadvantages. To exploit the enormous potential of the integrated sheet metal design, a paradigm shift in the basic understanding of product development processes has to be induced.

3 Properties of Products

3.1 Internal and External Properties

Conventional product design starts with the clarification of the design task. It is a process of variation and selection over different phases by adding product properties with every step and becoming more concrete [6]. In comparison to the step-by-step enrichment of product properties over the different phases of the pyramid model [7, 8], a new algorithm-based approach is introduced. Usually, a design process starts with market and customer needs, often articulated vaguely, incompletely and inconsistently. But an algorithm-based approach needs precisely defined parameters and relations between them. A first requirement for a successful algorithmization, therefore, should be to develop a well defined vocabulary and terminology, and to analyze physical models and existing products regarding their external and internal properties.

The most important aspect is the fact that products can be completely defined by so-called internal properties, which correspond to a vast set of external properties [9]. The requirements-list describes the properties or feasible areas of properties the customer is looking for (e.g. “reliability”). These demands cannot be established in a direct way by the engineer. The engineer has to choose and specify parameters which are related to the demands, but can be established in a direct way (e.g. material and geometry). These parameters are the internal properties. In short: The designer has to choose internal properties in such a way that the external properties are met.

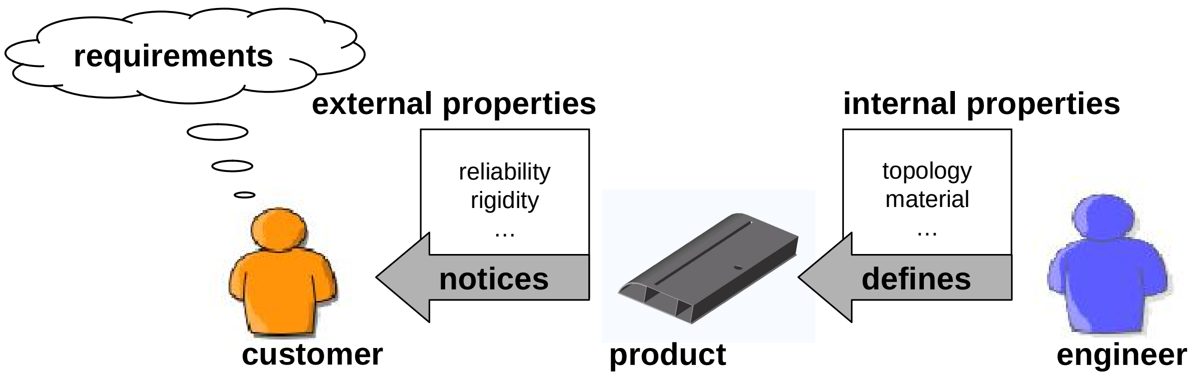

Figure 3. Correlation of Requirements, External and Internal Properties

In the early phases of product design, many properties are determined by the engineer, often without the knowledge of their effects on the product properties in later phases (e.g. embodiment design). One does not know which properties will be changed by choosing certain functions or function structures to realize the product. 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 respect to the given requirements representing customer and market needs?

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 to do 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 certain "property-network".
This approach is quite similar to what Suh calls "Axiomatic Design" [10] or is also described as "Characteristics-Property Modelling" [11].
Engineering design is based on the interplay between "what we want to achieve" and "how we choose to satisfy the need" [10]. According to Suh, external properties can be understood as the functional requirements which are mapped on the design parameters, i.e. the "how we want to achieve it".

3.2 Property-Network

Currently, the transformation of the costumer 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 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. Some attempts to assemble such a list are known, e.g. VDI 2225, but they have not been successful [9]. It seems more realistic to expect a domain-, branch- or even product-specific property-network, e.g. a property-network for designing linear flow splitted 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.
In doing so, vague costumer requirements have to be transformed into a standardized set of requirements, which will then be linked properties of the product (figure 4). Product properties will also be linked to each other from left, the more dependent properties (e.g. P_1) (external properties), to right, the independent properties, which can be determined directly by the engineer (P_{112}). The network illustrates which properties are linked and depend on each other.

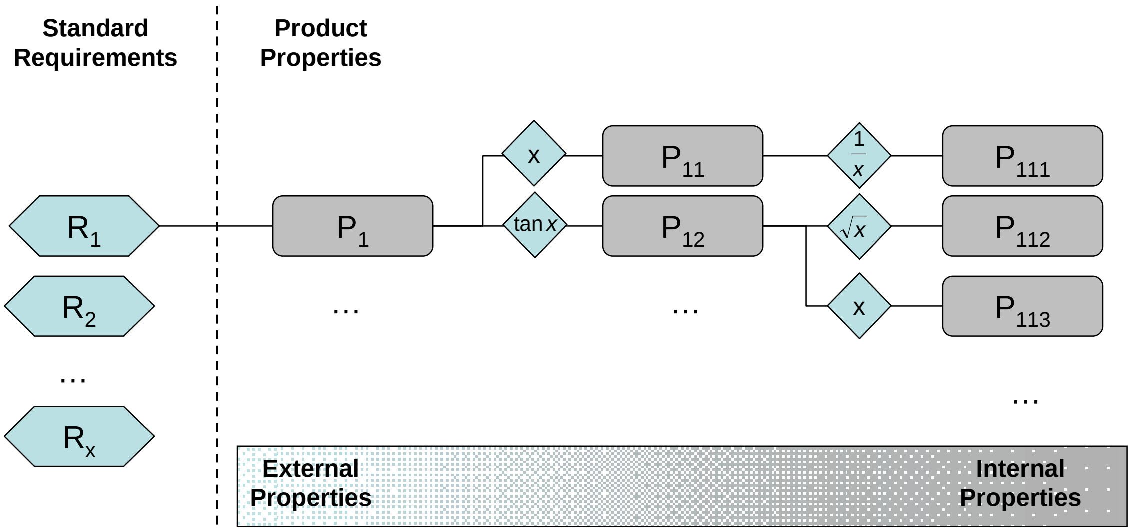

Figure 4. Property-Network

Going from right to left would be a so-called synthesis. The product's internal properties are to be determined based on the requirements. Each chain represents a new alternative to change internal properties to meet the costumer 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.

3.3 Property-Network of a Poster Stand

The property-network of a profile structure, the base of a poster stand [12], described in this paper uses this concept for settling equations, which relates certain standard requirements to product properties. This finally leads to internal and therefore adjustable properties for the engineer. By taking just three requirements into account, a complex property-network is generated (figure 5). Therefore, known physical models, such as the balance of forces and the balance of momentums, have been taken into account.

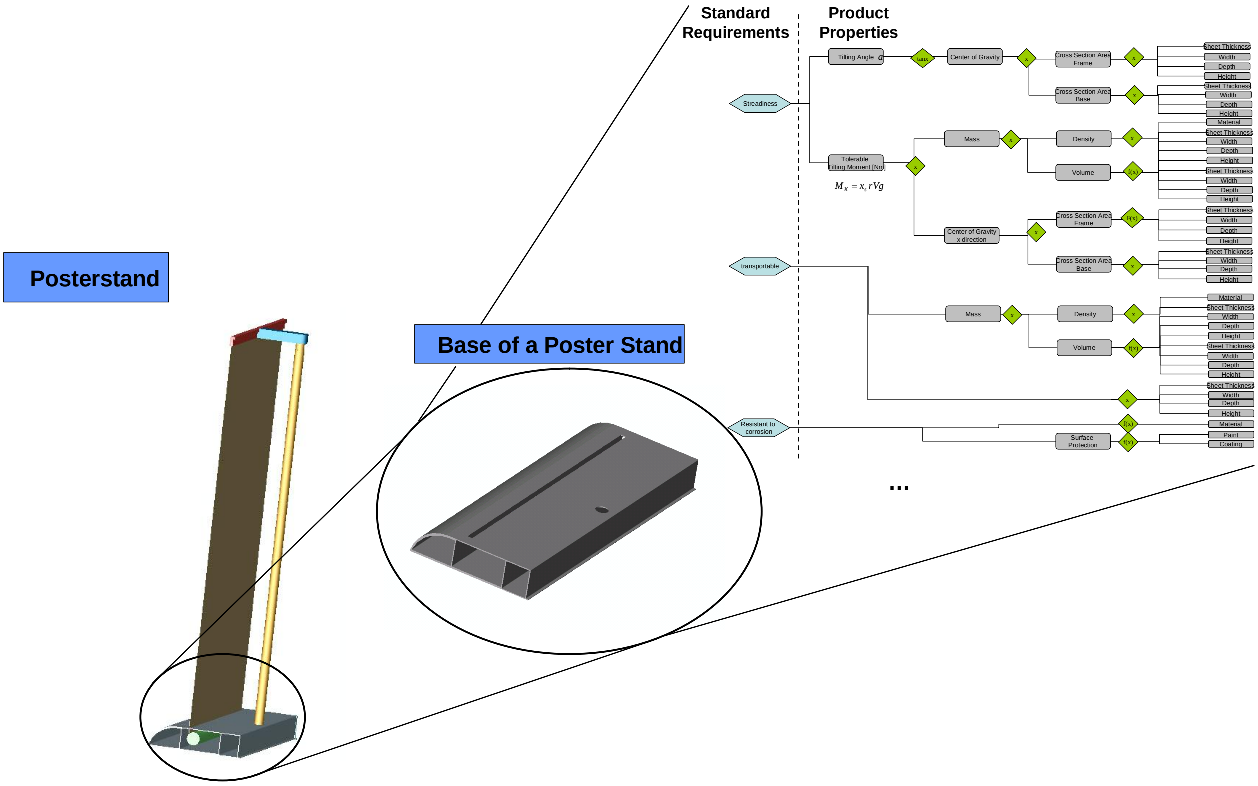

Figure 5. Poster Stand and Property-Network

Among other things, the standard requirement steadiness is taken into consideration (figure 6). The property-network of the base of a poster stand provides insight into the connection and correlation of properties. To improve the *steadiness* required of the poster stand base, one could either raise the *tilting angle* of the base or increase *the tolerable tilting moment*. The tolerable tilting moment is caused by external forces and is just great enough that the resistance points of an edge at the base leave the floor, and the resistance is reduced to zero.
Exemplarily, the chain to improve the steadiness of the base and therefore the whole poster stand is illustrated in figure 6. As shown in this network, the *tolerable tilting moment* is split up into *force* which is multiplied by a lever which is equal to the *center of gravity in x direction*. So, one possible way to increase the tilting moment would be through an extended lever and/or an increase in the force. But these are both properties which cannot be determined by the engineer in a direct manner. We have to trace external properties back to alterable internal properties.

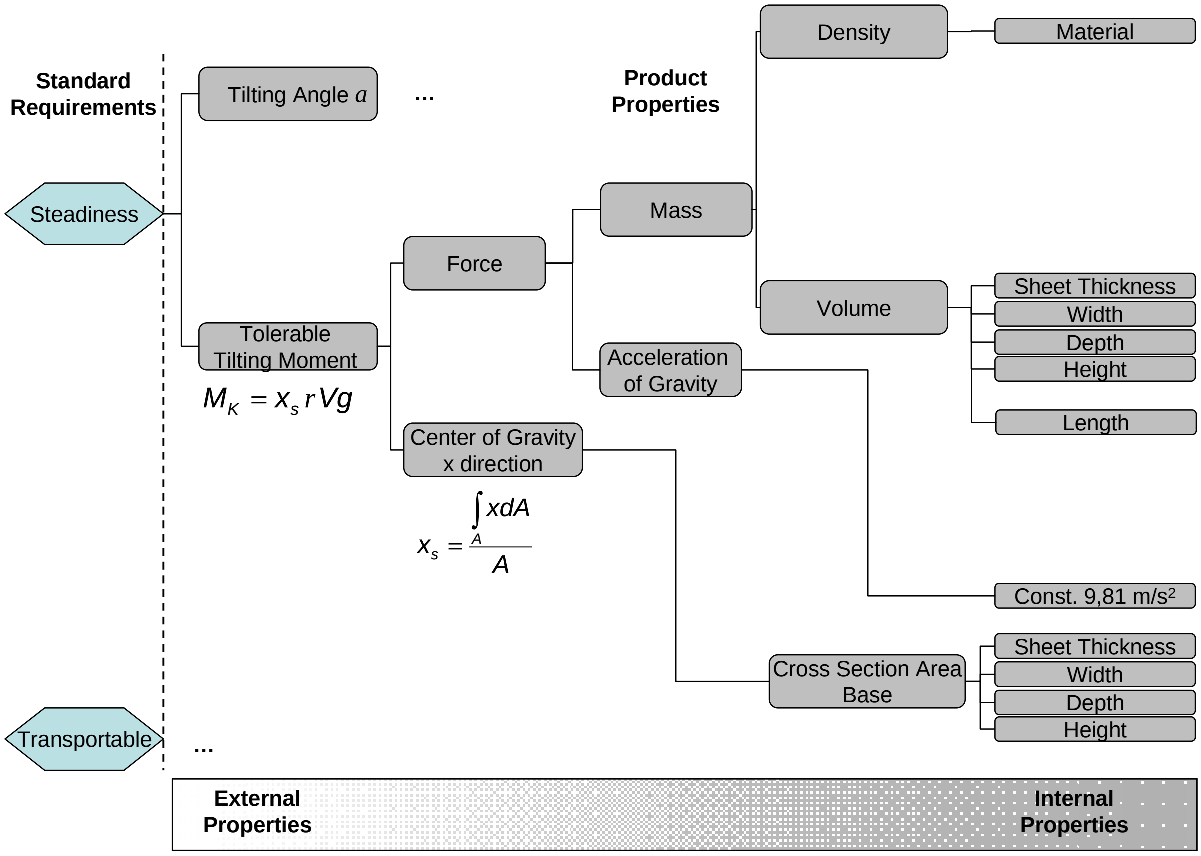

Figure 6. From Steadiness to Geometry

The *force* is split up and consists of the *mass* of the base profile and the *acceleration of gravity*, which is constant, as long as one stays on earth. The *mass* is made up of the *density* of our *material* and the *volume*, which is the area of the *cross-section* multiplied by the *length*. All these internal properties, e.g. material and geometry, can be modified and chosen directly. This network can be grasped by humans when just one standard requirement is involved, but it becomes incomprehensible with increasing complexity, i.e. when conflicting requirements occur and customer demands are taken into account.

3.4 Mathematical Optimization of a Cable Conduit

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.

A general mathematical optimization of internal properties does not exist to date. This is due to the absence of adequate studies about coherencies between customer wishes, requirements and product properties. As was shown for branched sheet metal products, many relationships between external and internal properties can be represented in a property-network and expressed in terms of a functional equation (figure 7). Starting with the demand to design a stable cable conduit, the network shows the interrelationship between product properties.

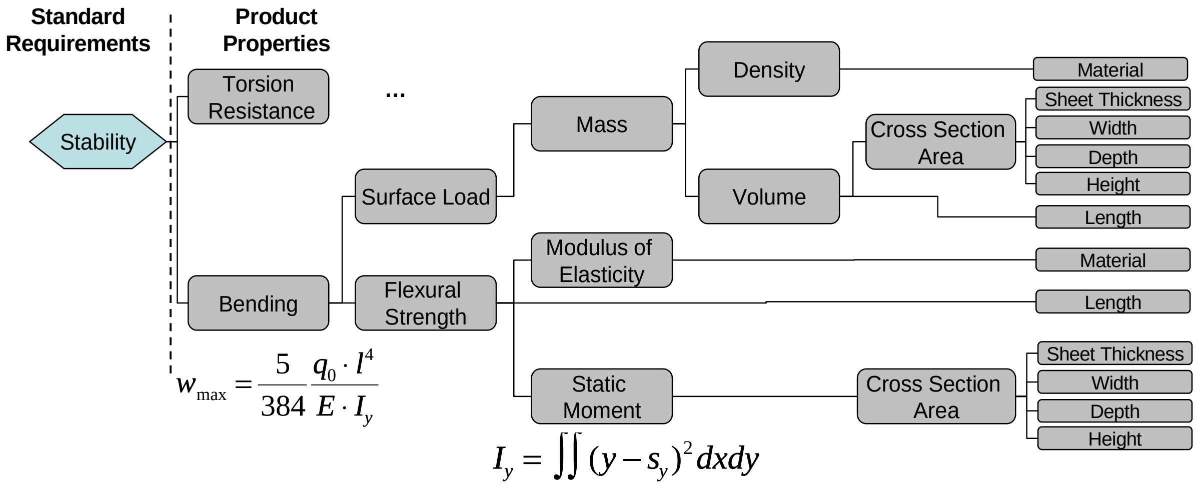

Figure 7. Property-Network of a Cable Conduit

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 profile. These equations are often non-linear, such as elasticity or heat transfer, and make the corresponding mathematical model most complex and highly difficult to solve [13]. To find feasible solutions very quickly, the mathematical optimization process is broken down into two stages.

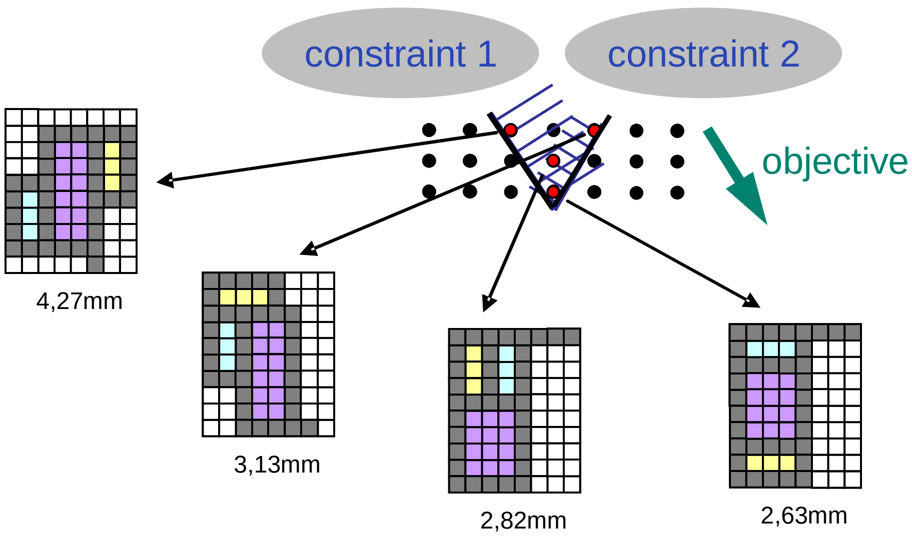

Figure 8. Generating feasible topologies and evaluating them

The intention of phase one is to calculate the overall topology of the product by solving a rough mixed-integer programming (MIP) model with linearized functional relations [13]. In mathematical optimization, product properties can be understood as constraints and objectives. In figure 8, the black dots represent the whole field of different solutions, each black dot a single new solution. Constraints, such as that all channels have to be closed to channel fluids, reduce the field of different
t solutions and define them. Solutions that simultaneously fulfill each of the constraints can be considered a feasible solution for the design task, posed by the hatched space between constraints 1 and 2.

If the feasible solution is not unique, all feasible solutions can be evaluated by objective functions, such as the minimum bending of the profile structure (figure 8). This will lead to the best solution for the design task.
In stage two, a more detailed product geometry should be obtained by solving a non-linear continuous shape optimization model. The case study was carried out to obtain insight into the feasibility of computer-based algorithmization of the early phases of design.

4 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 approach for the early phases of design, and therefore ongoing work in the CRC 666, will consist, on one hand, of a more elaborate description of properties and their relationship to each other in the form of 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, etc. Further research has to be done.
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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