LINEAR FLOW-SPLIT LINEAR GUIDES: INFLATING CHAMBERS TO GENERATE BREAKING FORCE

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ABSTRACT

The linear flow-splitting technology developed within the Collaborative Research Center (CRC 666) “Integral Sheet Metal Design with Higher Order Bifurcations” offers new options to manufacture innovative products. Especially using the technology to continuously produce linear guides is focused in this research. With linear flow-splitting and linear bend-splitting, chambered steel profiles provide possibilities to integrate functions into linear guides.
In this contribution, an approach to develop functions for linear flow-split linear guides is presented. Basing on calculation models and property networks, optimized solutions can be created while design modifications can be derived from the property networks. These property networks are very well suited to present an easy overview over the so called “set screws” with which the fulfillment of the requirements can be influenced. The approach also includes the validation of the calculation models and the functionality with finite element models and experiments. The approach is explained on the example of the function “clamping”.

Keywords: linear motion guides, product development, property network

1. INTRODUCTION

Within the CRC 666, new massive forming processes for sheet metal are developed and researched. These new technologies enable the production of novel chambered steels profiles that show special properties. These properties predestine the components to be used in linear guides that can be produced in integral style.
In this contribution, the development of a clamping function for linear flow-split components is shown. A systematic approach is chosen to achieve optimized solutions for the functions and modifications. Therefore, the property networks developed in the CRC are generated to describe the effect used to fulfill the clamping function. Property networks show independent and dependent properties with their corresponding relations in a manageable manner. In the property network, the function’s “set screws” become visible which allows the designer to derive design modifications to simplify or improve the functionality.
With the chosen approach in this study, an optimized solution for the desired function is found while the approach is usable in the process chain of the CRC.

2. BASICS OF THE NEW PRODUCTION TECHNOLOGIES

In the following section, the newly developed core technologies researched in the CRC concerned with “Integral Sheet Metal Design with Higher Order Bifurcations“ are presented. In specific, linear flow-splitting and linear bend-splitting are explained. Both of these production technologies are massive forming processes for steel at ambient temperature that can be used for continuous production with potentially up to 100 meters per minute [1]. A schematic of both processes, linear flow-splitting to the left and linear bend-splitting to the right, is displayed in Figure 1.

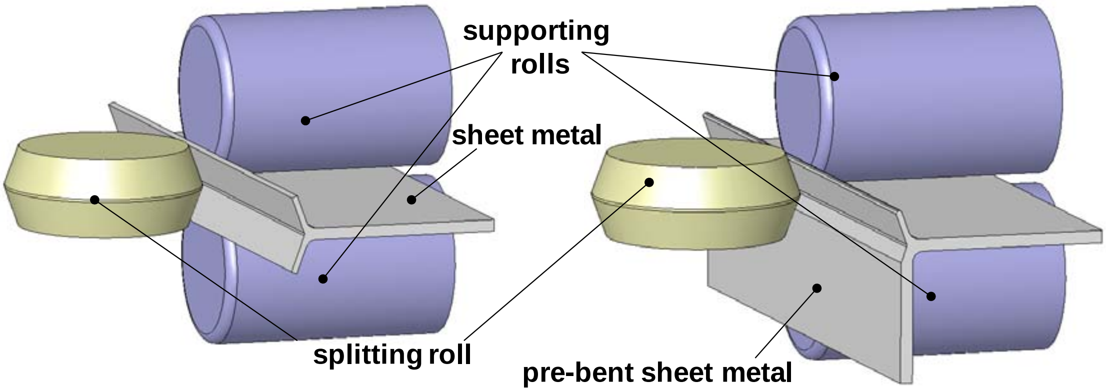

Figure 1: Schematic of the linear flow-split and linear bend-split processes

In the beginning of the process, the sheet metal is rolled off of a coil. During the linear flow-splitting process, the sheet metal band is fixated and guided by two supporting rolls above and below the sheet metal while the splitting roll splits up the coil's edge as seen in the left of Figure 1. This process occurs simultaneously on both sides of the band's edges. Thereby, the characteristic Y-shape of the two created flanges develops [2]. The depth of the splitting and thereby the length of the flanges is incrementally increased over several linear flow-splitting stands. Today, flanges with a total length of 20mm can be created without damaging the material [3].

Linear bend-splitting is relatively similar compared to linear flow-splitting. However, two major differences between the processes exist. First, linear bend-splitting requires pre-bent sheet metal as input. The bending edge is the contact point for the splitting roll as displayed on the right of Figure 2. Secondly, in contrast to linear flow-splitting, the process is only conducted on the one bending edge of the material while the other side (not shown in Figure 2) needs to fixated towards the force. A further difference is that linear bend-splitting can be used to create flanges anywhere in the material as long as the material can be bent in that place. Linear flow-splitting can only create flanges on the material's edges.

If combined with roll-forming, the new technologies enable the production of bifurcated steel structures as shown in Figure 2.

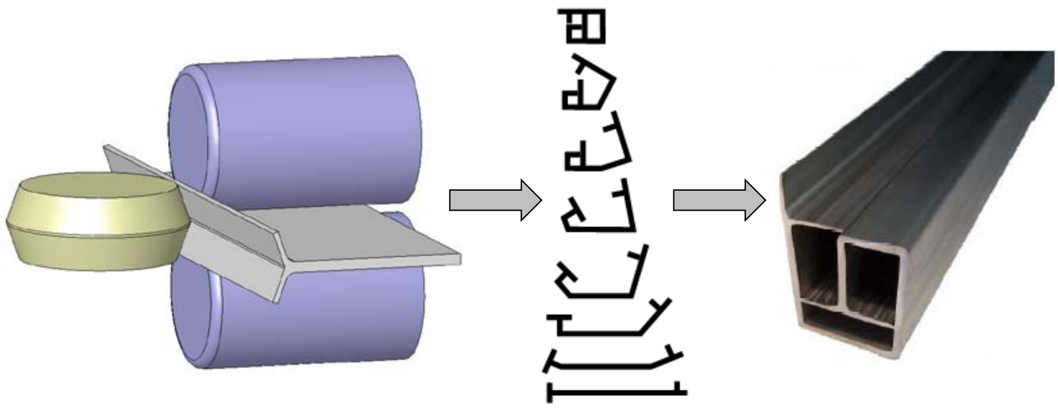

Figure 2: Bifurcated structures with the linear flow-splitting, flower diagram according to [4]

The geometry of the three-chambered profile as shown in Figure 2 is achieved by using linear flow-split material to roll-form the final geometry. Thereby, the whole product is produced in integral style. In the above scenario, the linear flow-split component's characteristic Y-shaped flanges have been modified to a 180° and 90° opening angle as shown in the middle of Figure 2. Additionally, adjacent processes as laser-welding and milling can be used prior to, between or after the linear flow-splitting process. In the three-chambered profile above, the chambers could be welded shut or holes, for e.g. connections, could be induced into the material. The inclusion of these processes into the process chain to be used integrally is also researched within the CRC.

The flanges of linear flow-split and linear bend-split components have similar technologically-induced properties resulting from the massive forming processes. First of all, the microstructure at the flanges has an ultra fine grained continuum [5]. This results in an increased hardness and lower surface roughness in comparison to the base material [6]. Thereby, the hardness is falling gradually towards the backside of the flanges. As preliminary tests revealed, the flanges additionally have an increased rolling contact and sliding contact fatigue-life [7]. Evidently, these properties predestine the linear flow-split flanges to be used as rolling contact surfaces.

These technologically induced properties make the new components very eligible to be used in linear guides. Moreover, there are further advantages resulting from the technology. For once, the created bifurcated structures have a high area moment of inertia and therefore a high stiffness while being rather light compared to full material which common rail guides are made of. This provides stability while also offering potential for light weight design. The continuous production of linear flow-split components and their eligibility to be used as rolling surfaces, straight from the integral production without further effort, provide a potential cost advantage over traditionally produced linear rail guides. Another advantage is the chambered structures of the linear flow-split profiles, since they can be used as “vessels” for additional functions. This could give linear flow-split linear guides a functional benefit which, combined with the production in integral style, could present a unique selling point.

Besides the obvious technological benefits of linear flow-split components for linear guides, the wide areas of application including various shapes and different degrees of technology for linear guides as well as their wide price span offers a large market and therefore also a large variety for possible problem solutions that the new linear guides could target. The ultimate goal for innovative linear guides from linear flow-split components should be to provide high quality functional guides for comparably low costs. For the conducted research, the main orientation has been ball rail guides.

In the following section, the idea for function integration into the chambers of linear flow-split profiles used in linear guides is further described. Due to the functional benefit of an innovative, integrated function, an attractive product can be created. Mainly produced in integral style, a “clamping” function for the newly developed linear guides is created. Possible fields of application for such a function could be an emergency stop or positioning tasks.

3. INTEGRATION OF THE CLAMPING FUNCTION

The integration of the clamping function is the goal of this function integration. The application of a breaking force can be solved in different ways that could be produced in integral style with the new technology. The chosen solution for the analysis is to create the breaking force by clamping a part of the sled between to inflated chamber walls of the rail, thereby creating friction that decelerates and eventually stops the sled. The inflation of the chamber wall is performed with pneumatic pressure. Therefore, the chamber of the linear flow-split rail needs to be sealed by welding.

3.1 Classification of properties

The multitude of design options for the embodiment of the function requires a systematic approach for design to find an optimized solution. The approach is based on the modified property classification developed in the CRC. The basics of the property classification are presented in Figure 3.

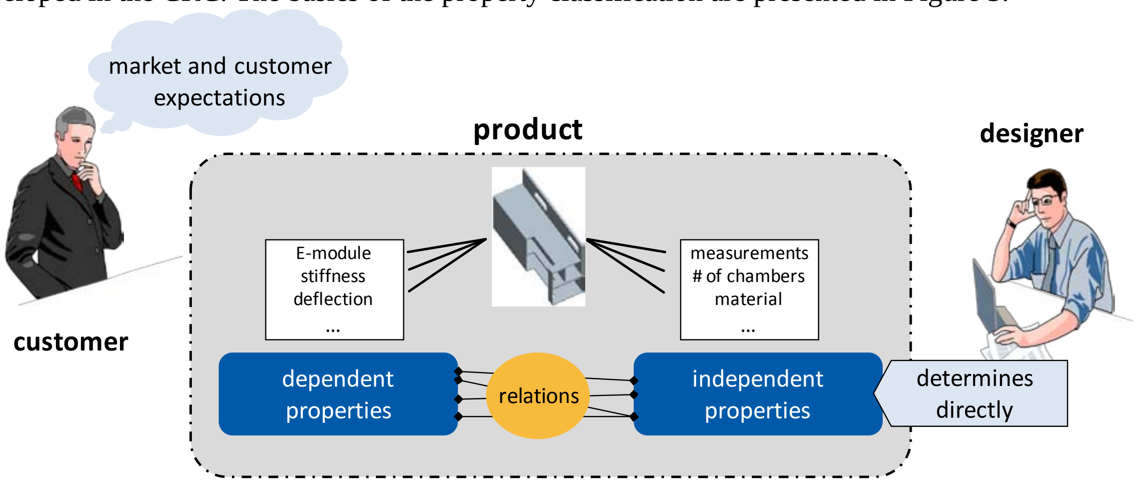

Figure 3: property systematic in the CRC 666

The above shown property classification assumes that the customer has certain expectations towards a product that he perceives as a whole. Opposite to the customer is the designer who can determine the product with a certain sets of properties while other properties can only be influenced over the connections with the influenceable ones. In the following, the properties that the designer can influence are called independent properties. Independent properties are e.g. the number of chambers or the material. Further, the properties that can only be influenced over independent properties are called dependent properties. Dependent properties are for instance the E-module or the deflection. [8]
If the dependent and independent properties as well as their relations are known, they can be displayed in a property network. From the property network, a designer can receive an overview over the influenceable and non-influenceable properties. The independent properties represent the so called "set screws" that the designer can turn to fulfill the customer's requirements according to the constraints regarding the functionality.

3.2 Approach to design functions for linear flow-split components

The general course of action of the here presented approach to design functions for linear flow-split components is shown in Figure 4.

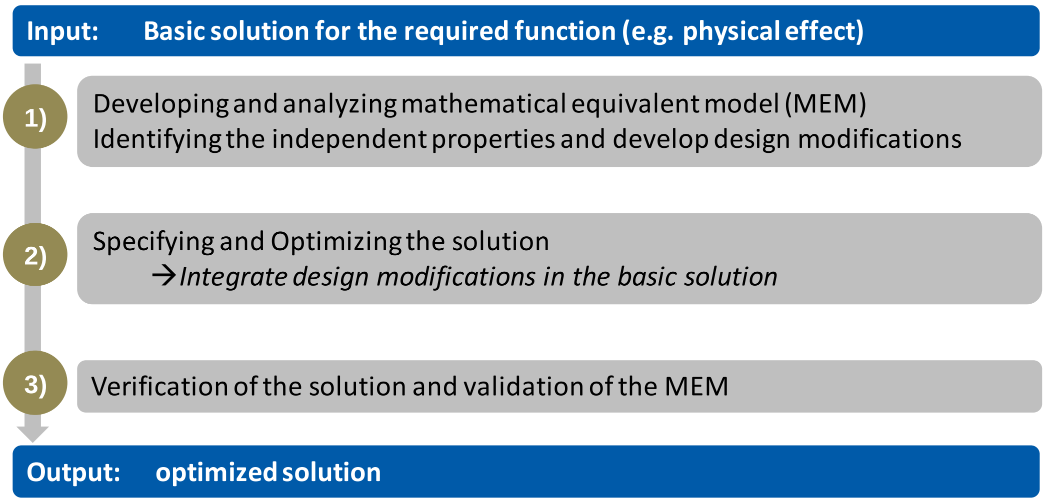

Figure 4: Approach to generate an optimized function for linear flow-split components

The required input for the approach is a feasible solution for the function as e.g. the physical effect.
Based on the input, the first step of the approach is to formulate a mathematical equivalent model (MEM) that displays the relevant dependencies between properties, sometimes partially simplified. Normally, the MEM is based on physical models that are often used in engineering. Furthermore, the independent and dependent properties and their corresponding relations are compiled and the according property network is spanned. With the knowledge of the independent properties for the fulfillment of the function, the feasible solution that was used as input is varied and modified so that a simplified or improved functionality is generated. The goals from this first step are the preparation of an MEM for the optimization as well as the development of design modifications with regard to the function fulfillment.
In the second step of the approach, the solution is specified and optimized. With the help of the MEM, a mathematically possible solution for the function is determined and then optimized with regard to the constraints. Modifications generated in the first step should be implemented into the MEM if otherwise the validity would be put in question. If the MEM should no longer be usable due to the design modifications, it needs to be adapted accordingly or the occurring error should be estimated with the help of the measurements from the third step. The results of the second step are a solution based on the MEM as well as the implementation of design modifications either by reformulating the MEM or by fault estimation.
In the third step, the function and the MEM are validated with the help of finite elements simulations and test rigs. Thereby, it is determined how well the simplified MEM is representing reality and how good the developed solution fulfills the desired function.

The steps of the approach can be used iteratively until no better solution can be found. Due to the variety of possible design measures and the determination of the physical principle as input, it cannot be assumed that a global optimum is found. However, the developed result represents an optimized solution.

3.3 Analysis of the chamber inflation and determination of the breaking force

As described above, the application of the breaking force is achieved by inflating two chamber walls in the rail, thereby clamping a part of the sled due to the created pressure. The active principle that is used to inflate the chamber walls is pneumatic pressure. A schematic of the function is displayed in Figure 5. The geometry of the rail and the sled is abstracted to only show the relevant areas for the function.

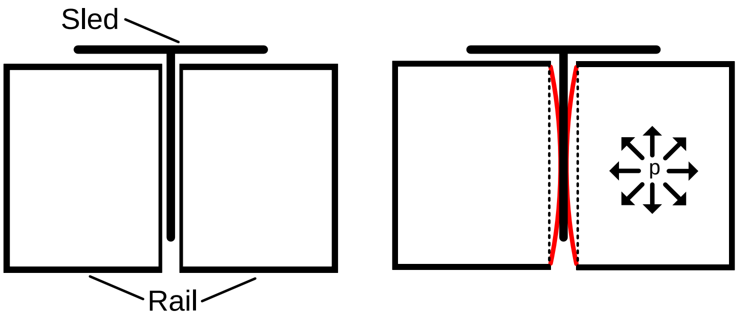

Figure 5: Schematic of the function principle

As shown in Figure 5, a part of the sled called “flag” is clamped between two expanding chambers of the rail, thereby creating the breaking force. According to the approach, a MEM is formulated to describe the effect in a simplified way. The MEM should include all the properties with high relevance to the fulfillment of function. As a point of origin, the simple chamber geometry shown in Figure 6 is used.

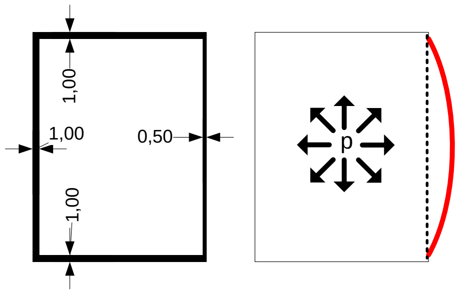

Figure 6: Regarded cross section of the chamber to formulate a MEM for the inflation process

Figure 6 shows that the regarded cross section of the chamber is a simple rectangular geometry with one wall thinned out to half the thickness of the base material. The biggest movement is to be expected at the thinnest chamber wall. To calculate the deflection of this wall, beam theory is used. Effectively, the deflection of a beam under an area load is used to approximate the movement due to inflation. In doing so, only the thinnest chamber wall is regarded. The basis to develop the MEM from beam theory is shown in Figure 7.

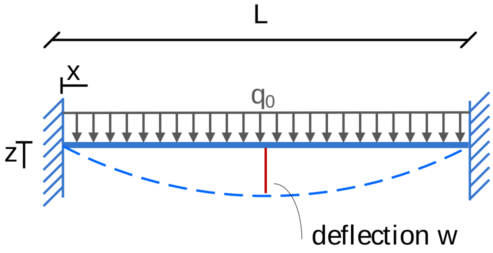

Figure 7: Abstraction of the chamber wall to apply beam theory

As displayed in Figure 7, a beam model with fixed support on both ends was chosen to represent the chamber wall. The biggest deflection is in the middle of the beam at *L/2*. The assumption that the inflation of the chamber can be approximated with the deflection of the beam is the basis for the calculation of the breaking force. To calculate the breaking force, first, the maximum deflection of the beam under the area load resulting from the applied pneumatic pressure is determined. Then, the necessary area load for the chamber wall to tangentially touch the sled's flag is determined. With the difference of those area loads, the length of the flag and the contact surface of flag and wall under maximum pressure are used to determine the breaking force. These calculations contain simplifications which are not further specified at this point. Nonetheless, it needs to be mentioned that the calculation error increases towards the ends of the beam. However, the following results constitute that the essential influence factors have been considered. Considering the aspired pressure range from one to six bar with further restrictions for the chamber wall length with up to 50mm, the MEM provides adequate results.
Results from the MEM regarding breaking force and deformation are shown in Table 1.

Table 1: Results for breaking force and deformation from the MEM

pressure (bar)	force (N)	deformation (mm)
1,5	59	0,15
2	95	0,2
3	190	0,27
4	275	0,39
5	490	0,49
5,5	530	0,54

This procedure complies with a part of the first step of the developed approach.

3.4 Development of the property network

In the following, the property network derived from the before formulated MEM is presented. For simplification, the property network displayed below only shows the properties that are also represented in the MEM. The property network is displayed in Figure 8.

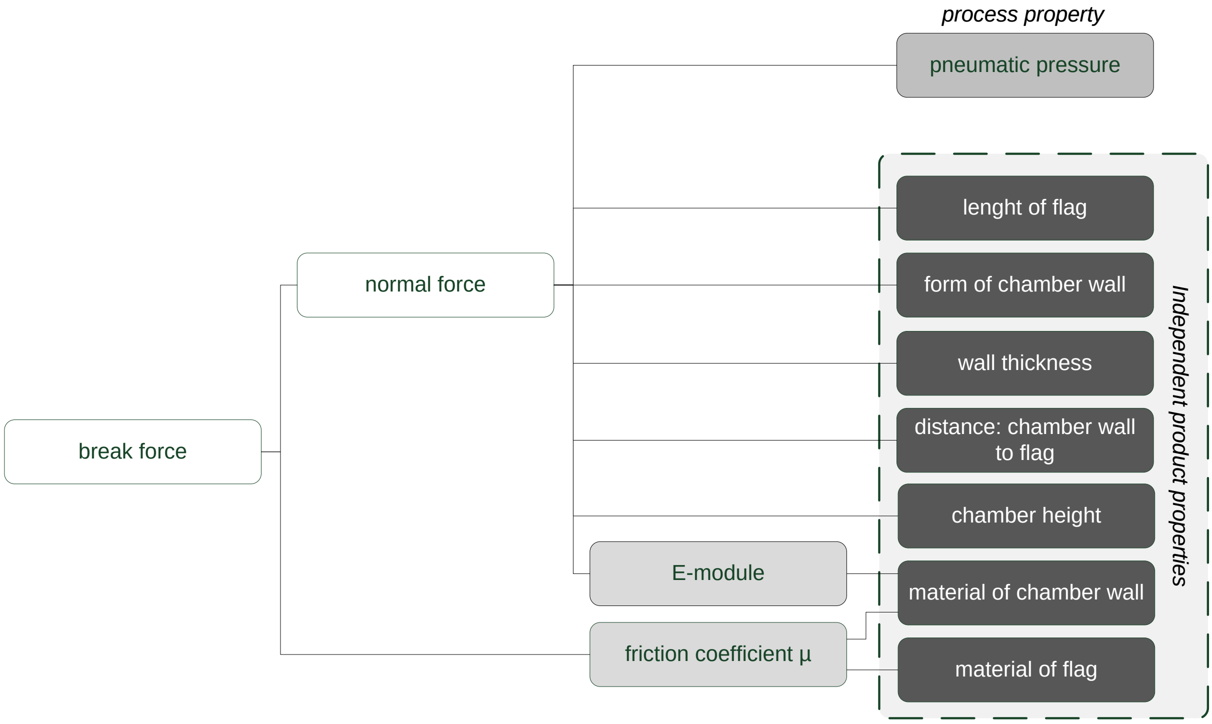

Figure 8: Property network based on the MEM

On the right side of Figure 8, the independent properties are displayed while the dependent properties develop to the left eventually resulting in the breaking force that is required. In contrast to the other

independent properties, the independent property on top on the right side is not a product property but a process property. In this case, process properties cannot be used to derive design modifications. On the other hand, all other independent properties can be modified to ease or improve the functionality. Especially geometric modifications regarding the form of the chamber wall will be present later.
The benefit of this approach is the clear identification of the “set screws” for the designer which allow to systematically developing design modifications. These enable the designer to overview and widen the solution area for the desired function. With the development of the property network, the first step of the above presented procedure is finished.
The design modifications that were derived from the property network are presented in a later passage. The specification and optimization is not presented in detail since it is essentially depending on the restrictions that are derived from the application that the function was chosen for. Based on these restrictions, the specification and optimization of the function can be achieved with the equivalent model.

3.5 Validation of the MEM with experiments

To validate the results of the chosen MEM based on beam theory, a test rig has been developed. It allows measuring the occurring forces and deformations due to the inflation process under a given pressure. The test setup is displayed in Figure 9.

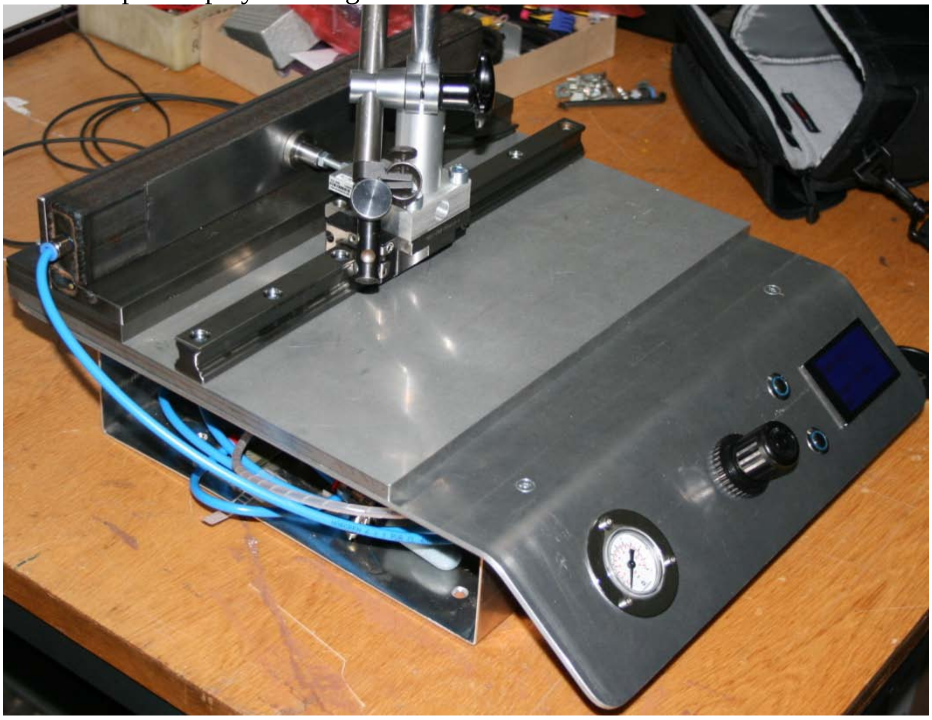

Figure 9: Test setup to measure force and deflection during inflation

Averaged measurements of the occurring forces and deformations during inflation of the chamber are listed in Table 2.

Table 2: Force and deflection of a chambered steel profile depending on the pressure

pressure (bar)	force (N)	deformation (mm)
1,5	65	0,17
2	100	0,22
3	208	0,3
4	301	0,41
5	513	0,52
5,5	581	0,57

Comparing the results of the MEM with the experimental data, a deviation of less than ten percent is perceived. However, the deviation is relatively small in the preferred pressure range for the function of one to six bar.
The data documented in Table 2 was measured on a rectangular profile where one chamber wall has been thinned out to 0,5mm, half the thickness of the base material. The material was removed from the outside of the chamber. However, linear flow-splitting would allow thinning-out the inside by first removing the material and then forming the geometry.
As shown in Figure 9, the deformation of the profile is constrained on two sides. The measurements were taken on the longer side of the rectangular cross section. It is reasonable to assume that the deformation on the shorter side of the profile is significantly smaller.
It is necessary to underline again that the MEM can only be used for this or similar cross section geometries. Design modifications to optimize the functionality were not validated and would probably only represent the real behavior insufficiently.
Regarding the comparison of the empiric and theoretic data, deviation also results from the neglect of the profile length in the direction of the translatory movement of the linear guide. This is based on the assumption that the inflated chamber wall regarded in the calculation is significantly larger than the shorter side of the cross section but simultaneously significantly smaller than the neglected length. The length of the real sample only partially reflects that assumption. Therefore, smaller experimental results for force and deformation can be assumed which corresponds to the collected data.

3.3 Validation of the MEM with finite elements

The validation of the MEM with finite elements simulations is important to check the compliance with the elastic yield of the material. Therefore, the geometry of the test sample was modeled in CAD and then transferred to a FE model. The analysis reveals critical areas in the inflation process which gives hints for an appropriate optimization in this direction. Since plastic deformation of the material is not desired, the elastic yield cannot be exceeded.
The results from the FE simulation with regard to the deformation of the geometry are found in Table 3.

Table 3: Results of the FE-analysis

pressure (bar)	deformation (mm)
1,5	0,187
2	0,25
3	0,375
4	0,5
5	0,625
5,5	0,68

Since the geometry of the FE model is ideal compared to the real sample, the results for the deformation in the simulation can be expected to be bigger which corresponds to the collected data. The same effect results from the chosen constraints of the simulation. Nonetheless, the result of the validation is that the deformation of the profile is adequately captured in the MEM and well within the elastic range. The MEM can therefore be used for the optimization within the desired pressure range and geometric restrictions.
With the validation of the equivalent model, the first iteration of the proposed approach is finished. When design modifications are considered, further iteration could provide a better solution to the task.

3.4 Recapitulation

The validation of the MEM shows that the real behavior of the chamber wall under the given constraints is adequately displayed. Those constraints especially determine the cross section geometry of the chamber. Additionally, the application scenario also constrains the pressure range. Accordingly, the MEM is not universal but only valid under the given restrictions. However, the testing revealed that the function can be integrated with regard to achievable deflection and forces without exceeding the material’s elastic yield. Moreover, the property network enables the designer to get a good overview of the properties influencing the functionality.

3.5 Design options derived from the property network

Based on the property network, the set screws of the clamping function were determined. In particular, these independent properties are the wall height, material thickness as well as the shape or the cross section of the chamber. The influences of the chamber height and the material thickness are known from the MEM. However, the variation of the cross section geometry of the chamber allows a variety of modifications that cannot be reproduced directly in the MEM's current form. To reproduce the following modifications in the MEM, it needs to be adapted appropriately. Only one of the derived modifications is presented here to demonstrate the potential of the proposed approach. This modification that is presented here targets the form of the chamber wall. It is shown in Figure 10.

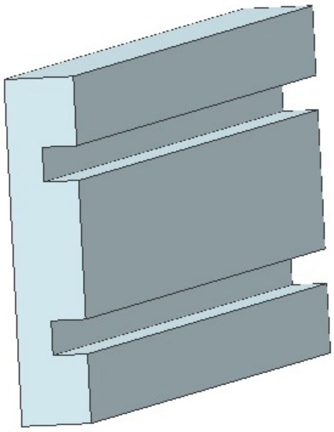

Figure 10: Options for design modifications

In Figure 10, there are only two grooves milled into the chamber wall instead of the whole wall being milled off. This reduces the milling effort and is more material efficient. Additionally, the deflection curve develops a more leveled contact area for the sled's flag. Another option could be a geometry analog to a bellows with wich bigger displacements could be achieved. If a solution with a reversed active principle is aspired, a bellows-like geometry with grooves instead of forming areas could provide a solution.
As both of the exemplary described modifications massively change the geometry of the chamber, the mathematical equivalent model as determined above does no longer comply and needs to be modified to provide equivalently accurate solutions.

4. CONCLUSION AND OUTLOOK

The presented contribution clearly underlines the strengths of the linear flow-split technology which also underlines the potentials of the technology for practical applications.
The outlined approach for the optimization of functions by providing a MEM for mathematical optimization and developing a corresponding property network to derive design modifications has proven to be efficient. The property networks show the relations of separate influencing factors and provide an insight into the subject even with more complex connection matrices. Especially for designers, the “set screws” to create a well working function become obvious. The weakness of the approach lies in the predetermination of the active principle. However, intelligent design principles based on the technological possibilities and strengths can help to chose proper working principles from the start.
With regard to the development and optimization of the function and geometry it becomes evident, that the new production technologies provide plenty of options. The possibilities range from modified semi-finished parts as tailored blanks to process extensions as flexible linear flow-splitting. The optimization of functions has to be conducted not only in experiments but also with the help of FE-simulations. Of great importance is a further form optimization of the chamber where the embodiment of the transitions between thinned-out and base material as well as critical areas in the edges has to be researched.
Future research focus will lie on the further integration of new and innovative functions into linear flow-split linear guides in integral style.

ACKNOWLEDGMENTS

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REFERENCES

[1] Vucic D. And Groche P. Erweitern der Verfahrensgrenzen beim Spaltprofilieren. *Tagungsband 1. Zwischenkolloquium Sonderforschungsbereich 666*, TU Darmstadt, 2007, pp. 67-72

[2] Groche, P. and Vucic, D. Multi-chambered profiles made from high strength sheets. *Product Engineering, Annals of the WGP, Vol. XIII/1*, Hannover Germany, 2006

[3] Jöckel, M. Grundlagen des Spaltprofilierens von Blechplatinen, Shaker Aachen, 2005

[4] Groche, P., Ludwig, C., Schmitt, W. and Vucic, D., Herstellung multifunktionaler Blechprofile. *wt Werkstatttechnik online 10-2009*, 2009, pp. 712–720

[5] Bohn T., Bruder E. and Müller C. Gefüge und mechanische Eigenschaften von Spaltprofilen aus ZStE500. *Tagungsband 1. Zwischenkolloquium Sonderforschungsbereich 666*, TU Darmstadt, 2007, pp. 97 – 102

[6] Groche P., Vucic D. and Jöckel M. Basics of Linear Flow Splitting, *Journal of Materials Processing Technology 183*, 2007, pp. 249–255

[7] Lommatzsch N., Gramlich S. and Birkhofer H. Linear Guides of Linear Flow-Split Components. *International Conference on Research into Design – ICoRD'11*, January 2011, Bangalore, India, pp. 439-446

[8] Birkhofer, H. am Wäldele, M. Properties and Characteristics and Attributes and…- an Approach on structuring the Description of Technical Systems, *Applied Engineering Design Science - AEDS 2008*, 2008, Workshop in Pilsen, Czech Republic, pp. 19–34

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