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TRANSFORMING OF TECHNOLOGICAL FINDINGS FOR A BETTER DEVELOPMENT OF BRANCHED SHEET METAL PRODUCTS

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ABSTRACT
This paper proposes a preliminary classification structure of the existing technological findings of linear flow splitting. The process model of Heidemann was used to analyze the technological findings. The analysis resulted in a classification into processes and objects. Furthermore, criteria like the type and geometry of the semi-finished product, sub-processes, engaged machine components and specific conditions for the employed material are established. Based on this disposition, an ontology concept is established. The classification is exemplarily applied to a product sample manufactured using linear flow splitting and used as a basis for transforming technological restrictions into design parameters. In the first approach, a set of manufacturing restrictions is identified. By means of these manufacturing restrictions, the influence of the technological findings on the mathematical optimization is exemplarily shown. In order to compute the optimal way to produce a given profile, a Mixed Integer Program (MIP) is set up and solved using methods from discrete optimization. Here the goal is to approximate the given product geometry as closely as possible, while incorporating all manufacturing restrictions, such as the maximum flange length. If the technological findings result in a new maximum for the flange length, this information enters the process in the form of new constraints for the MIP. In the case of the flange length, they are incorporated into the MIP via cutting planes.

Keywords: Design, transformation, classification, mathematical optimization

1 INTRODUCTION

Recently, a new sheet metal forming technique, called linear flow splitting, has been developed, which, in combination with traditional techniques such as roll-forming processes and joining techniques, allows for the production of multi-chambered structures with thin-walled cross-sections [1]. One main advantage of the linear flow splitting technique is that the profile can be produced with less joining, and without laminating material or heating the semi-finished part. In order to shorten the design process of a multi-chambered profile, it is important to integrate the technological findings of the production and the evaluation of the manufactured product in a structured and systematic way, providing mathematical optimization. The focus of our research is on detecting the influence of technological findings, i.e., data and results of the evaluation of the manufacturing processes and the developed profiles, concerning the continuous manufacturing line in the product design process [2]. The objective is to reduce the number of iterations made by product designers, while improving their products during the design process in general, hence ensuring the development period. The manufacturing line comprises machines which realize linear flow splitting, linear bend splitting, high speed cutting, roll forming, laser welding, and cross cutting of the profiles. All manufacturing processes influence the properties of the produced profiles. The evaluation of the profiles gives a precise description of their properties. To integrate this information into the product development process, it is necessary to classify the technological findings appropriately and to transform them into design parameters, which can be used as input for the mathematical optimization. In mathematical optimization, varying parameters can lead to completely different outputs, i.e., in our case, to different shapes and production lines. Thus, it is important to have close and fast interaction between technological findings and the optimization process which finds the optimal way to unroll the profile.

2 TECHNOLOGICAL FINDINGS OF LINEAR FLOW SPLITTING

Linear flow splitting enables the forming of bifurcated profiles made of sheet metal in integral style without joining, lamination of material or heating the semi-finished part. The semi-finished part is plain sheet metal, which is transformed at ambient temperature by a specific tooling system, which increases the surface of the band edge by using obtuse angled splitting rolls and supporting rolls (Figure 1). These rolls induce high hydrostatic compressive stresses in the local forming zone during the process [3]. Due to the enormous compressive stresses, the formability of the material increases, which allows for the realization of large strains. The moving, semi-finished part is formed by the tool system in discrete steps up to a profile with the final shape (Figure 1). The produced parts are characterized by increased stiffness, high surface hardness and low surface roughness on the upper side of the flanges of the bifurcated object. Using a following roll forming process, new multi-chambered structures with thin walled cross-sections can be realized [4].

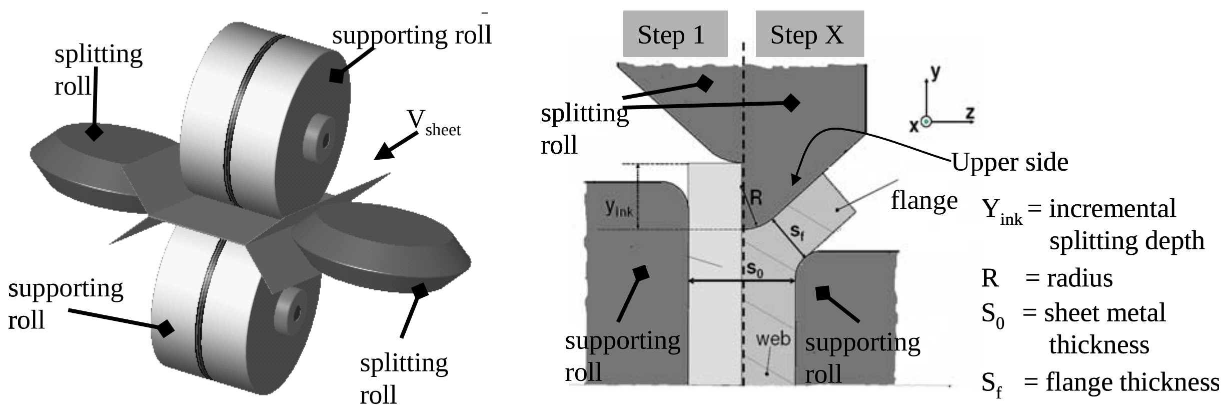


Figure1. Principle of linear flow splitting

The bifurcations are caused by a surface enlargement of the sheet metal's band edge during the forming process and form a profile containing two flanges and a web at each side of the sheet metal. The surface beneath the splitting roll is defined as the upper side of the flange (Figure 1). There is a sizeable set of factors influencing the linear flow splitting process, e.g. the sheet metal thickness S_0, the working radius of the splitting roll, the working radius of the support roll, the incremental splitting depth y_{ink} and the flange thickness S_f.

In addition to the linear flow splitting for realizing bifurcations, a high speed cutting tool is integrated in the continuous manufacturing line for placing dimensional elements, like drillings and gashes, into the moving semi-finished part. A laser welding tool is used to close the profile if necessary. In the future, a linear bend splitting tool system for creating flanges directly out of the sheet metal and not by enlarging the surface of the band edge, will be added.

3 CLASSIFICATION OF TECHNOLOGICAL FINDINGS

To shorten the design process of such profiles, it is important to integrate the technological findings of the production and the evaluation of the manufactured product in a structured and systematic way, providing mathematical optimization. The enormous quantity of data produced by the manufacturing and evaluation of linear flow splitting, high speed cutting, and linear bend splitting processes and the generated profiles first necessitates a classification to provide the data to the mathematical optimization. Regarding the variation of the representation of the information e. g. protocols, diagrams, series of measurements, etc., these findings need to be standardized. This factor first necessitates a classification of the existing technological findings of the linear flow splitting process, in preparation of the transformation into design parameters for the mathematical optimization.

3.1 Analysis of the Data by the Process Model of Heidemann

The manufacturing and the evaluation generates a large quantity of information. There is information about the sheet metal, the construction and operation mode of the participating machines, the evaluation data of the manufacturing process and the manufactured profiles. To find an appropriate representation, the data was first analyzed by the process model of Heidemann [5]. The process model of Heidemann characterizes a process as the temporal transfer of an object from an initial state to a final state. In the case of linear flow splitting, sheet metal as a semi-finished part is transformed into a bifurcated profile. Figure 2 shows the transformation of the object's properties from the initial state to the final state. The most obviously modified property is the shape of the sheet metal, and therefore the geometrical measurements, e.g. sheet metal thickness, flange length, flange width. On the first glance, the process model reveals that the description of linear flow splitting needs to be differentiated into processes and objects. The sheet metal is regarded as an object transformed into a bifurcated profile, which represents a second object. The process is the cold forming of the sheet metal by inducing compressive stress.

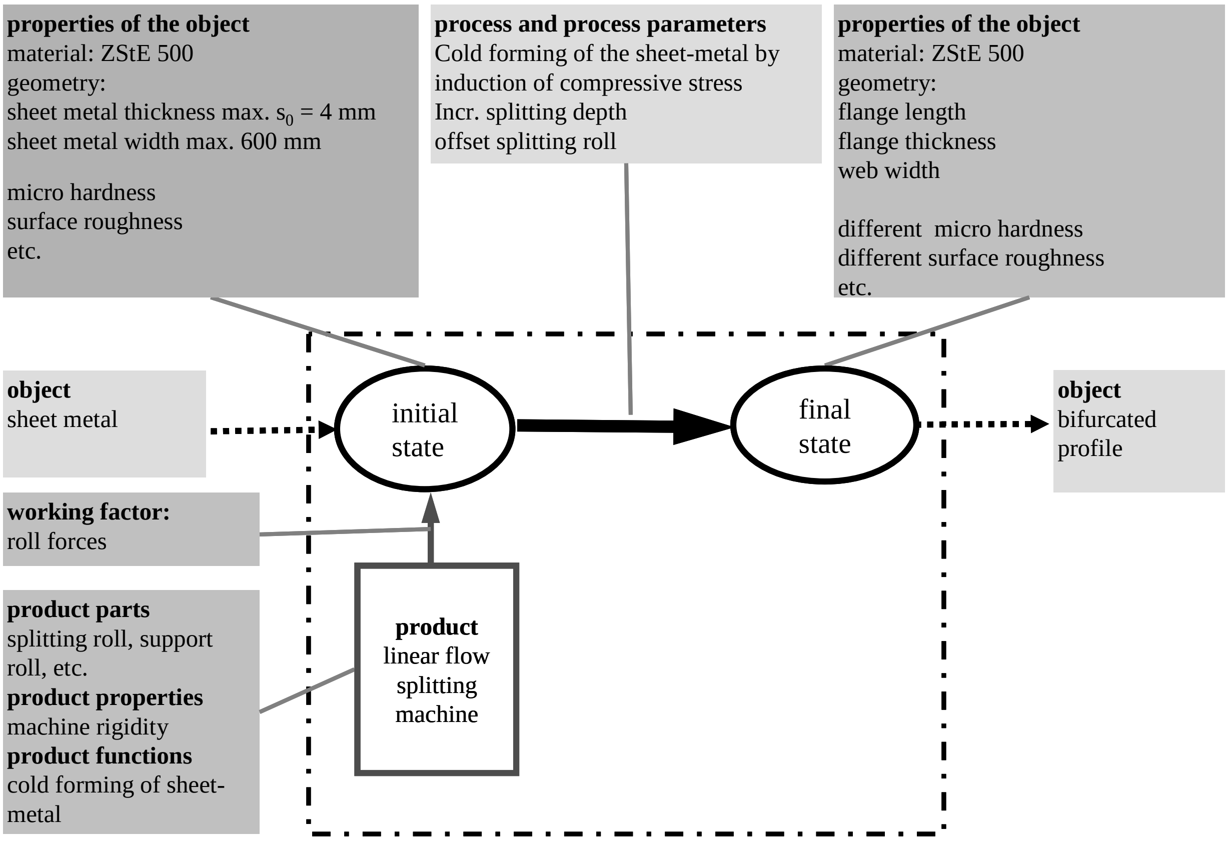


Figure 2. Process model of Heidemann

The process is induced by the linear flow splitting machine, which contains components like the splitting roll, the support roll, and so on, and is steered by parameters like the incremental splitting depth and the position of the splitting and supporting rolls. The linear flow splitting machine represents a so-called product in the process model, which affects the process using the working factor roll force in y-direction.

The process model leads to an initial classification into objects and processes. In this connection, the objects are the machines and their components, the semi-finished part and the bifurcated, the manufacturing methods are considered processes.

3.2 Classification Structure

In order to allow for effective data management, engineers invest time in analyzing, organizing, classifying and labelling the available data and the technical resources. The process of information management strongly depends on how knowledge needs to be structured [6]. The technological findings must be organized, in order to process and store a large amount of data to provide to the transformation into design parameters. Therefore, one has to consider processes, on the one hand, and objects of different types, on the other hand. Furthermore, it is indispensable to respect the relations between objects and processes.

The classification of technological findings is based on two main concepts: processes and objects. At first, a taxonomy approach seems to be an appropriate method to classify technological findings data.

A taxonomy is a classification of concepts described by terms according to inheritance (is-a relationship).

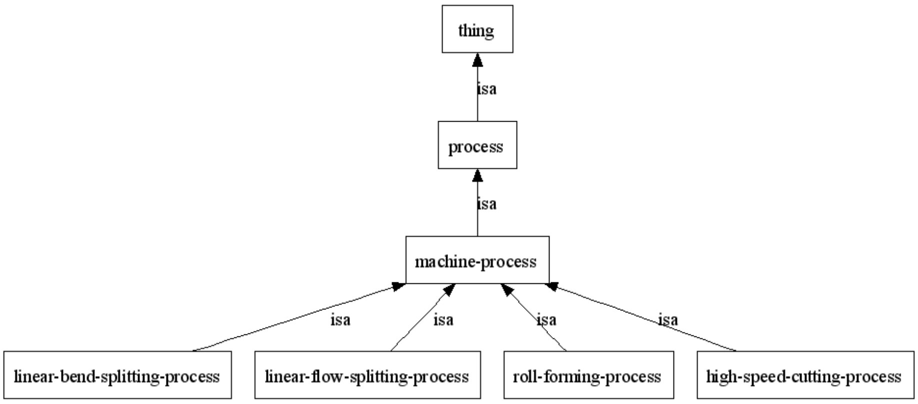


Figure 3. Taxonomy for the process concept

Figure 3 shows the taxonomy for the process concept. The process concept aims to represent the manufacturing processes operated by the continuous manufacturing line, while producing profiles in integral style. In the hierarchy, concepts representing processes such as linear flow splitting, high speed cutting and roll forming are direct descendents of the “machine-process” concept, which represents the processes realized by machines. The concept “machine-process” is a descendent of the concept “process.” Although the taxonomy approach provides a clear and efficient classification of the objects, it is important to not only classify the objects, but also to classify the relations between the objects and the processes. Taxonomies are only able to represent relationship between concepts based on inheritance. Another potential classification approach uses a thesaurus. A thesaurus is a classification of concepts defined by vocabulary, according not only to inheritance, but also to similarity and synonymy. Still, this approach was considered to be too simple, since the nature of relationships between the concepts of the technological findings domain is different from similarity and synonymy relations.
The appropriate classification approach for the technological findings domain should consider inheritance and non-inheritance based relationships between concepts, which might also have properties that are concepts themselves as well.

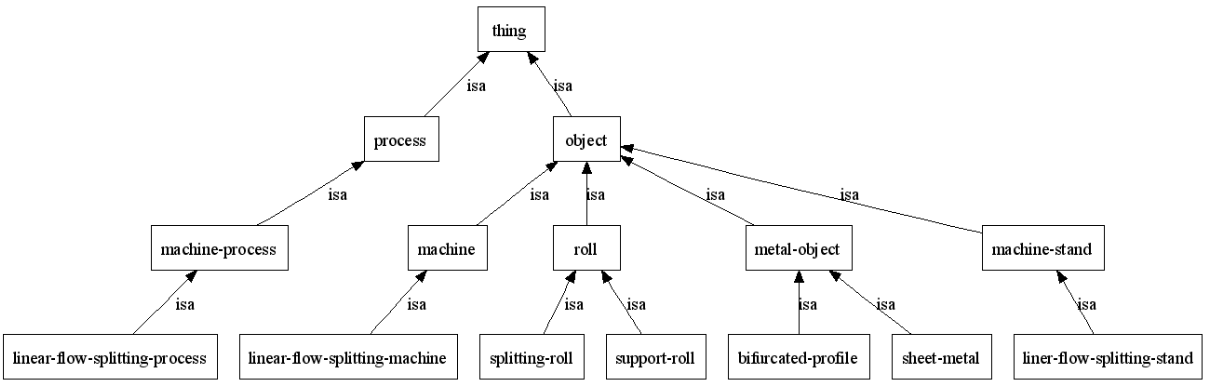


Figure 4. Taxonomy of objects and the linear flow splitting process

Figure 4 shows an enlarged classification approach for object and process concepts, only with regards to the linear flow splitting process. Although taxonomies are widely accepted in the research community for classifying data, taxonomies are too simple, and therefore inappropriate, for representing the complexity of the relationships existing in the technological findings of the manufacturing process of profiles made by linear flow splitting.
An ontology might be considered the most complete and powerful model for information representation [7]. In philosophy, ontology is the study of being and existence, in others words, it studies the basic categories of being and attempts to find what entities exist and what types of entities exist. In the computational sciences, ontology is an attempt to define an exhaustive and formal

hierarchy with respect to a particular part of the world (domain), containing all the relevant concepts, the relationships between them and the associated rules. An ontology model of a domain consists of a set of relevant concepts associated with their properties, extended with the relationships of different types (inheritances and non-inheritance based) between concepts and a set of associated rules.

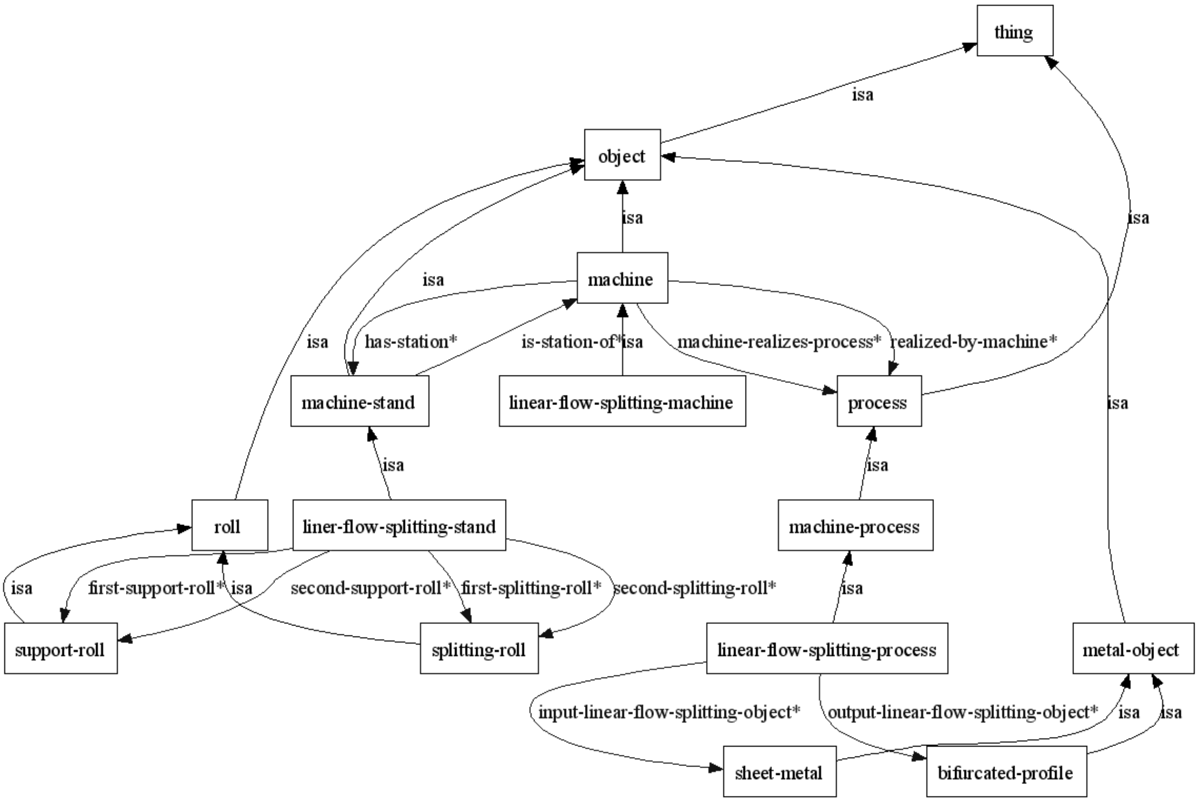


Figure 5. Approach of technological findings ontology

Figure 5 shows a model for the domain of technological findings. An example for an inheritance relation is that the support-roll is a descendant of roll, or that the linear flow splitting stand is a machine stand. A non-inheritance relation between objects and processes is represented by the realization of the linear flow splitting process by a machine. The ontology represents non-inheritance relations between objects as well. An example is that the linear flow splitting stand has two splitting and two supporting rolls as components.

Ontology models provide explicitly defined semantics to structure the data domain [8]. The data is then stored as instances of the ontological concepts. This approach allows for the modification and extension of the data structures, even during project execution, and creates the flexibility necessary for supporting creative design processes.

3.3 Transformation in Design Parameters

The classification of the technological findings' data serves as a basis for generating design parameters for the mathematical optimization. The maximum manufacturable flange length is an important input for the mathematical optimization, since it sizeably affects the optimal profile shape. Among the relations between the parameters of the linear flow splitting process, some can lead to an estimation of the maximum manufacturable flange length, depending on the material of the semi-finished part.

In order to determine the maximum flange length, a lot of parameters and conditions, like the incremental splitting depth and the position of the rolls, must be taken into account. To determine the influence of each of these parameters on the process, a lot of studies that have not yet been finished are required. Even with the knowledge of all of these studies, a precise estimation of the maximum flange length will be a very demanding process. The central issue is the three-dimensional material flux in the forming zone during linear flow splitting. Using a model that only considers two dimensions and disregards the material flux in the feed direction of the semi-finished part during manufacturing reduces the implication of the parameters.

The 2-dimensional model is based on the constant volume of the sheet metal during the forming process. The connection between the flange length and the splitting depth is linear. The flange length increases with the gradient of the quotient of the sheet metal thickness and two times the flange width by increasing splitting depth. The flanges begin to develop at a splitting depth of 0,75mm. This is due to an adaptation of the bent edge formed by material flux to the radius of the splitting and supporting rolls [9].

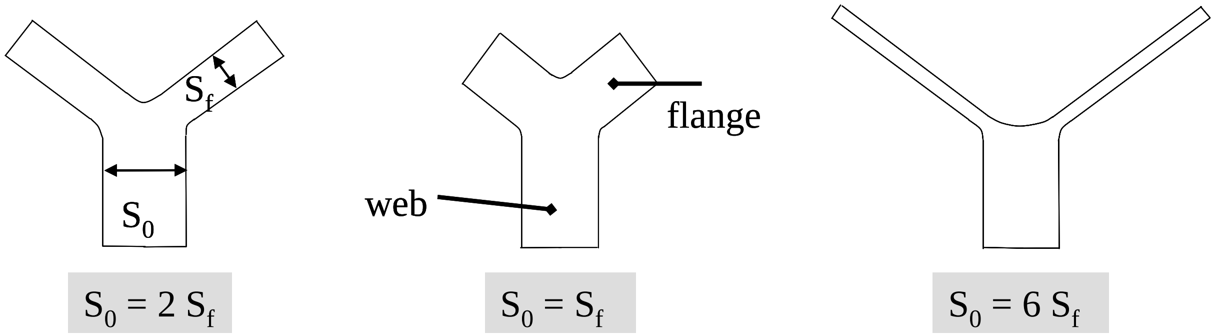


Figure 6. Different shape of bifurcations

Figure 6 shows a sketch of the influence of different ratio of sheet metal thickness and flange width on the final shape of the bifurcation.

4 MODELLING MANUFACTURING RESTRICITIONS IN MATHEMATICAL OPTIMIZATION

As mentioned in the introduction, the technological findings must be incorporated into the mathematical optimization process at an early stage, in order to avoid suboptimal results or results that are unfeasible. To illustrate how technological findings can enter the optimization process, the basic ideas of the model are given along with an example of how technological findings are transformed into parameters for the optimization process. Given a desired product geometry specifying the length l_e and thickness t_e for each line segment e of the component (Figure 7), the task of the mathematical optimization process is to find an unrolling, i.e., a way to produce the component, such that the given geometry is best approximated, when all manufacturing restrictions are taken into account [10].

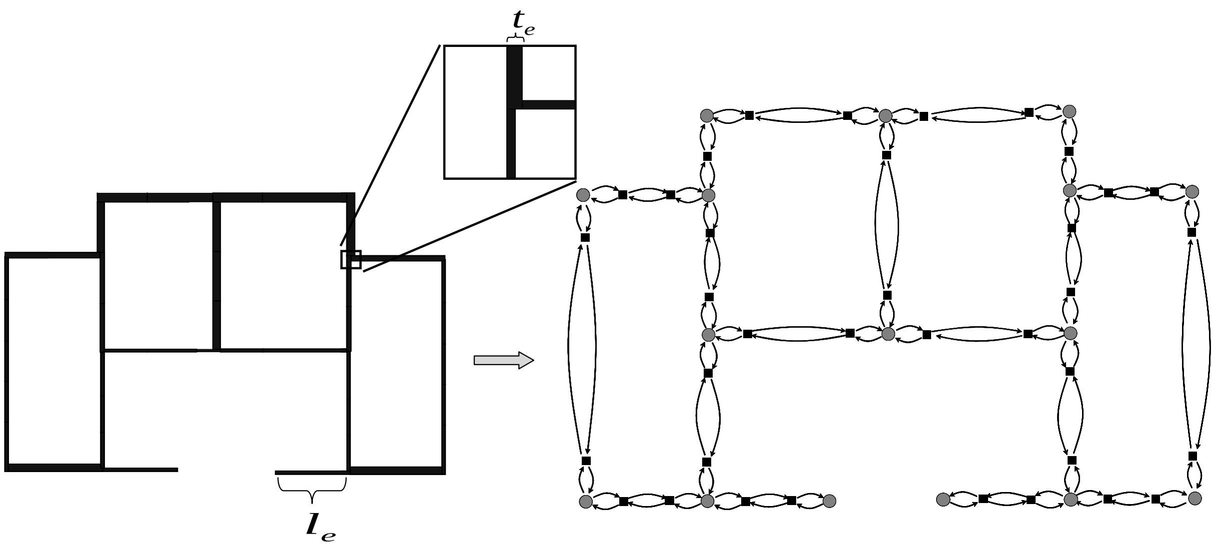


Figure 7. Desired geometry and resulting graph

4.1 Optimization Model

In order to find the optimal unrolling, first a graph $G = (V,E)$ is constructed that represents the component (Figure 7). Each corner point of the component can be manufactured by either a roll forming or a joining process. In case of a T-junction, there are several possibilities for how it can be manufactured (Figure 8).

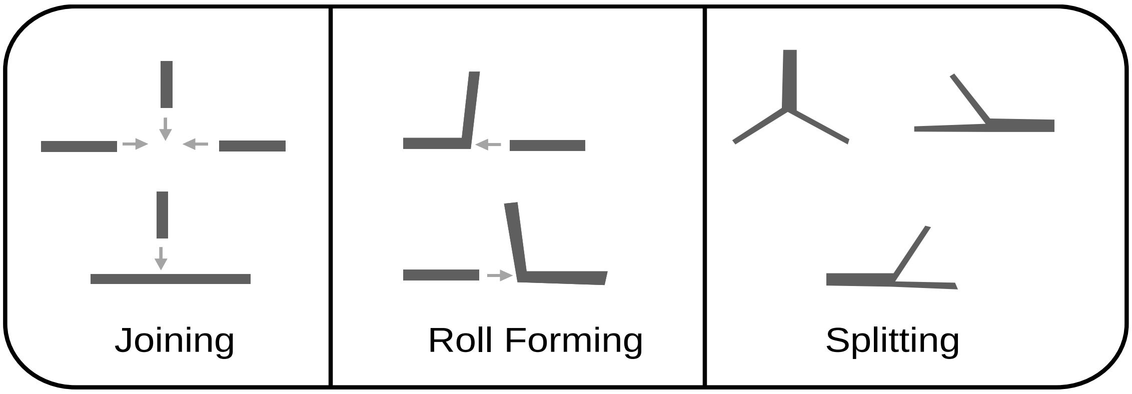


Figure 8. Technologies for T-junctions

Deciding on which technology to use for which intersection point has an immediate influence on the thickness of the individual line segments, as indicated in Figure 8. Therefore, the crucial point of the optimization process is to decide which technology to use for which intersection point, so that all manufacturing constraints are satisfied and the desired thickness is best approximated. Mathematically, this becomes the problem of finding a certain substructure of *G*, namely a Steiner arborescence [11], with an additional flow condition representing the thickness of the sheet metal. Depending on the form of the substructure that is computed, i.e., depending on which edges are in the solution, one can deduce which technology to use for the corresponding point in the component. For finding this substructure, a Mixed Integer Program (MIP) is introduced, which, among others, contains the following binary decision variables:

- $x_e = 1$ if edge *e* is contained in the solution;
- $y_v^t = 1$ if technology *t* is used to produce intersection point *v*;
- s_e denoting the absolute value of the difference between the suggested thickness and the actual thickness.

Here *v* and *e* are a node and an edge respectively of the graph, and *t* represents a technology. Note that one can encode the different technologies as numbers, and let *T* be the set of splitting technologies. Since the goal is to approximate the suggested thickness, the objective function can be written as

$$\min \sum_{e \in E} s_e \tag{1}$$

4.2 Modelling the Flange Restriction

There are a large number of constraints that must be addressed. They enter the model in the form of linear inequalities. In this paper, the focus will be on those constraints which are important for the restriction to which the length of the flanges is bound. This is handled in the following way:

The MIP is solved using methods from discrete optimization [12]. The assignment of the *y*-variables gives information on which technology is to be used at which intersection point, and the assignment of the *x*-variables tells us which edges of *G* are in the solution which is necessary for checking if a path is too long. If, in the resulting graph, there is a path *P* starting at a splitting node representing a flange that is longer than the maximal flange length *m_flange*, i.e.,

$$\sum_{e \in P} l_e x_e > m\_flange \tag{2}$$

a cutting plane, i.e. a linear inequality that forbids the flange to appear again in the next iteration is added to the model.

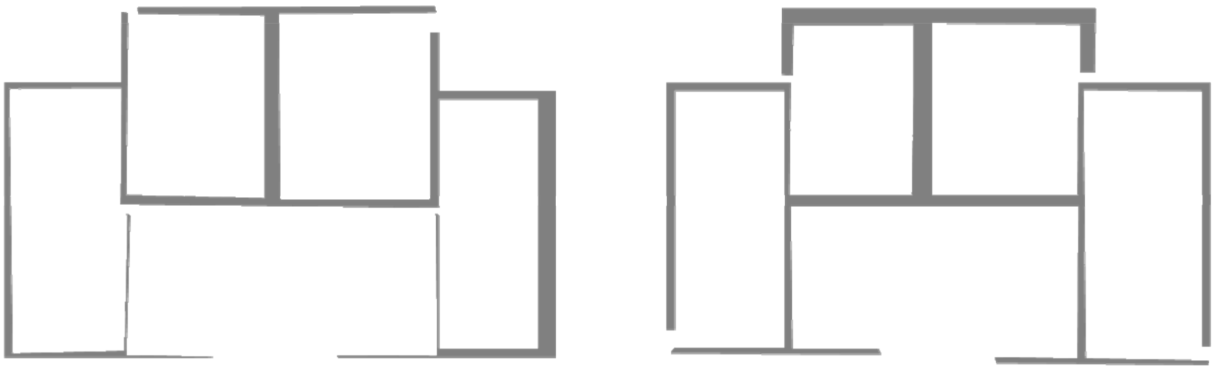
The cutting plane can be written as

$$\sum_{v \in P} y_v^t \leq \left| \{ v \in P \} \right| - 1 \quad (3)$$

This inequality ensures that the technologies of the intersection points on the path cannot be all chosen the same in the next iteration. Thus, there has to be at least one change in the choice of the technologies on the path, and therefore the flange will be shorter or not a flange at all in the next iteration.

However, the right hand side of the equation (2) must be specified, i.e., the maximal flange length. This strongly depends on the thickness of the flanges (Figure 6). So far, only the first case of Figure 6, where the sum of the thickness of the flanges equals the thickness of the web, has been considered in the mathematical model. Hence there might have been suboptimal solutions, since the mathematical model did not consider all possibilities that the new splitting process offers. In order to use all possibilities, the dependence of the flange length and thickness, which was elaborated in Section 3.3, has to be entered into the model. The information on the thickness of the flange enters in the assignment of the *s*-variables, and the information on the corresponding maximal length is encoded in the parameter *m_flange*. Introducing this into the model leads to an improved unrolling and thus to a better product design.

To illustrate the influence of the flange length and width, the example introduced in Figure 7 is considered. Figure 9 shows the optimal unrolling when the sheet metal can be centricly split ($S_0 = 2S_f$) only and b) the optimal unrolling when more information on the behavior of the relation between the flange length and width is available. In the latter case, the improvement considering the deflection denotes 13% in comparison to the first case.



a) $S_0 = 2S_f$ b) $S_0 = xS_f \quad x \in [1.5, 2]$

Figure 9. Output of the optimization process

5 CONCLUSION AND OUTLOOK

The combination of product design and evaluation provides the opportunity for better and faster product design. The established classification structure is the first step towards a methodology to introduce technological findings in the design process of a linear flow split product.

The linear flow splitting process is a new technology with great potential. Using the example of the flange length restriction, it was shown how technological findings from this process can be incorporated in the mathematical optimization process to obtain optimized geometries and production lines. The example presented in the paper illustrates the improvement that can be achieved by including technological findings in the design process. At the moment, the first continuously manufactured profiles are in the evaluation process. The evaluation will reveal a large number of technological findings, which again are transformed into design parameters and then include in the optimization model. To name a few, information on where to locate the welding seams in the profile or where to re-split a flange, particularly regarding the distribution of the increased micro hardness, is of major interest.

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