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A CONCEPT FOR A STRUCTURED DESCRIPTION OF PROFILE-STRUCTURES OF BRANCHED SHEET METAL PROFILES AS BASIS FOR AN AUTOMATED DESIGN PROCESS

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1. Introduction

The product development process of technical systems is strongly shaped by manual actions and decisions. Experience, intuition and acquired knowledge of previous problems are used to take these actions and decisions. In general, an experience-based approach quickly leads to workable solutions. Finding an optimum solution might require more effort.

In the context of Collaborative Research Center 666 (CRC 666) (German: Sonderforschungsbereich 666, SFB 666) methods and procedures that automate the product design process will be developed. The goal is an algorithm-based automation which ensures to find the optimal solution (global optimum) without additional work for designers. Beyond that, the generation of completely new, unexpected solutions will be expected.

The core element of the CRC 666 is composed of new forming processes called linear flow splitting and linear split bending. Linear flow splitting allows branched profiles to be formed out of sheet metal in integral style. The goal of the CRC 666 is to exemplify how branched sheet metal products can be designed automatically. The focus is on an overall view of product development and manufacturing so that positive product properties that result from the manufacturing process can be used for designing the optimal product.

1.1 Manufacturing branched sheet metal profiles by linear flow splitting

Branched sheet profiles allow to realise desired functions without consuming much space or material. Compared to plane components with the same mass they are much more resilient. In addition, closed cross-sections show heavy torsional stiffness. The branches allow designing multi-chambered profiles. The chambers can be used to realize different sub-functions, i.e. creation of insulating hollow space, cable ducts, conduction of gas, liquids or compressed air. So far, branched sheet metal profiles were mainly produced in differential style, i.e. by gluing, welding or similar procedures. Manufacturing those parts with integral style branches by using linear flow splitting has the advantage that very thin-walled profiles can also be produced. Due to the lack of or the small number of connecting pieces the profiles have less weak spots. A high accuracy can be achieved through transforming the semi-finished part at ambient temperature. Branched sheet metal profiles are lighter, they have a lower disposition to corrosion and a higher thermal conductivity [Jöckel 2005].

Linear flow-splitting is a massive forming process for the production of branched profiles in integral style. The semi-finished part is a sheet metal plan. It is transformed at ambient temperature by a specific tooling system which consists 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. The further processing of the split sheet metal by roll forming and bending procedures presents the opportunity to produce multi-chambered profiles with new cross-sections from sheet metal (figure 1). 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 [Groche 2006].

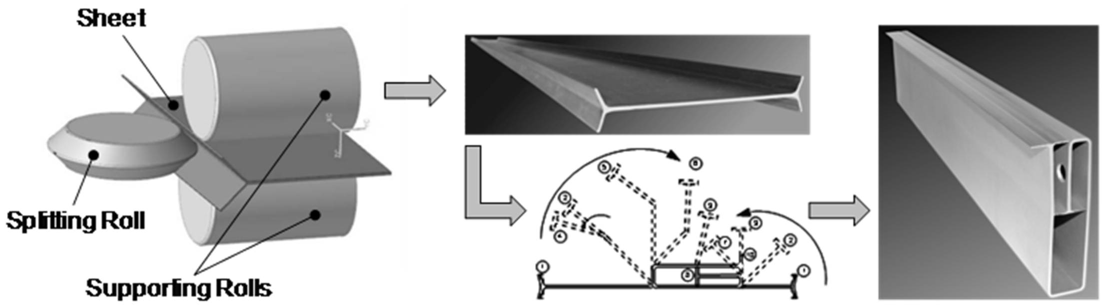

Figure 1. Manufacturing multi-chambered profiles

1.2 Profile-structures

Profile-structures are assemblies that are produced by assembling processes of branched sheet metal profiles. They are also characterised by a secure connection between the individual profiles which does not permit any movement between the parts. A very flexible application is given through the use of multi-chambered profiles in profile-structures; e. g. profile-structures can be passed around corners or barriers. There is also the possibility to connect multi-chambered profiles to branched profile-structures (alike tree structures). If the individual chambers are used as conduit, whole material-conduit-networks can be designed and produced in integral style. Thus the positive properties of the product resulting of the manufacturing processes can also be used for more complex tasks.

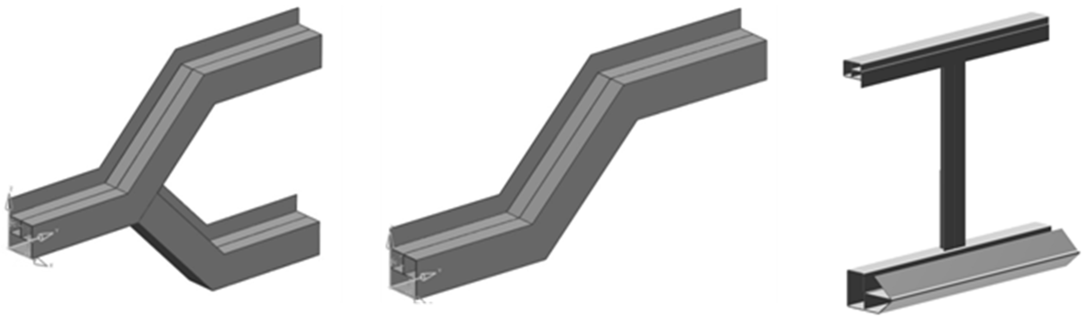

Figure 2. Profile-structures

2. Product designing as an optimisation of design parameters

According to the theory of properties technical systems are produced and used because of certain desired properties. Properties can be classified in internal and external properties. Internal properties are determined by designers directly. The external properties are the product‘s outwardly perceivable properties. The costumer can recognize and observe them. The designer can only influence them indirectly. [Hubka 1984] An external property is always the result of internal properties. According to this, product designing is to determine and optimize certain internal properties in such way that the required external properties of the product are met as closely as possible. Internal properties that are relevant for the mathematic optimisation are called design parameters [Wäldele 2009]. To automate the product design process the design parameters have to be identified and mathematic optimisation procedures have to be created.

3. Automated design of profile-structures

In the first period of the CRC 666 it was shown that the design process of cross-sections of branched sheet metal profiles can be automated. In this context only a few technologies that can easily be formalized were considered. In the second period the focus is on profile-structures. It is postulated, that the design process of profile-structures can also be automated.

4. Gradually optimisation of design parameters for profile-structures

A preliminary analysis of profile-structures revealed a large number of highly interconnected design parameters. The number and combination of design parameters are indicators of the object complexity. Profile-structures have a significantly higher object complexity shown by the comparison of profile cross-sections and profile-structures. The object complexity is based, amongst others, on the third dimension that needs to be considered and the higher number of degrees of freedom. In addition, regarding the manufacturing of the connection points between the profiles, far more technologies come into consideration. The distinct object complexity requires a gradual approach for the determination of design parameters. An established approach for complex problems is to start with creating abstract level requirements before gradually going into further detail.
Such an approach was developed by SFB 666 for the optimisation of cross-sections of multi-chambered profiles. It is based on division into three steps: topology, geometry and technology.
The first step is to optimise the (cross-sectional) topology by determining the arrangement of the chambers to a basic cross-section layout. The location and crossings of the chambers are defined. The result is displayed in a pixel grid. The fixed topology forms the basis for the optimisation of the geometry. Geometry properties as well as material properties are determined. In consideration of the equations of elasticity, the material is chosen (and thus modulus of elasticity, density, etc. determined) and the optimum sheet thickness is defined (Figure). In the third step, the calculation of the optimal unrolling will ensure that the designed profile is producible. A technology is selected on each crossing of chamber walls, which will be further referred to as intersection point (whether to 'join' or to 'split', figure 3).

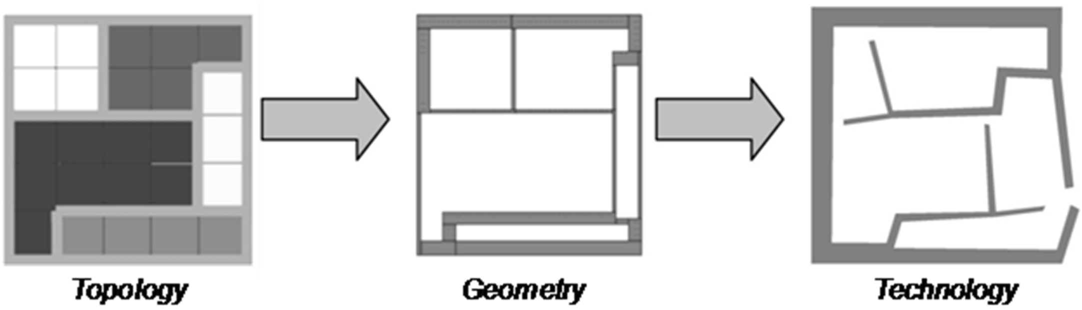

Figure 3. Topology, geometry and technology

In order to design profile-structures in an automated way, concerted steps have to be defined. Similar to the designing of profile cross-sections, geometry properties and material properties have to be determined for profile-structures and producibility has to be ensured. Below it is shown that the approach of the optimisation of cross-sections of multi-chambered profiles can, in principle ,also be applied to profile-structures.

4.1 Topology

First, the optimal topology of the profile-structure has to be found. This includes the cross-sectional topology and structural topology.

4.1.1 Cross-sectional topology

The number of profile-elements is determined by the structure topology. The optimal cross-sectional topology has to be found for every single profile-element based on a mathematical optimisation.

Mathematical procedures for the optimisation of the topology of multi-chambered profiles have already been developed by the CRC 666. The systematical search for a global optimum solution is based on modern methods of Discrete Optimization [Wäldele 2009]. These procedures can also be used to optimise the cross-sections of profile-elements of profile structures.
From a technological point of view, it makes sense to match the successive cross-sections because the individual profile-elements are interconnected. Thus, the cross-sectional topology is directly linked to the structural topology and to the technology. The design of symmetric cross-sections has the advantage of avoiding waste in the process of cutting. The two parts can be directly connected after the cutting and a 180 ° rotation around the longitudinal axis. The cross-sections fit together exactly (figure 4 left). An additional cut is necessary for non-symmetrical cross-sections and therefore material would be lost (figure 4 right). There are more examples that show the linking of topology and technology. Within the development or expansion of the optimisation procedures such linking and interdependencies have to be considered, for example in the form of iterations.

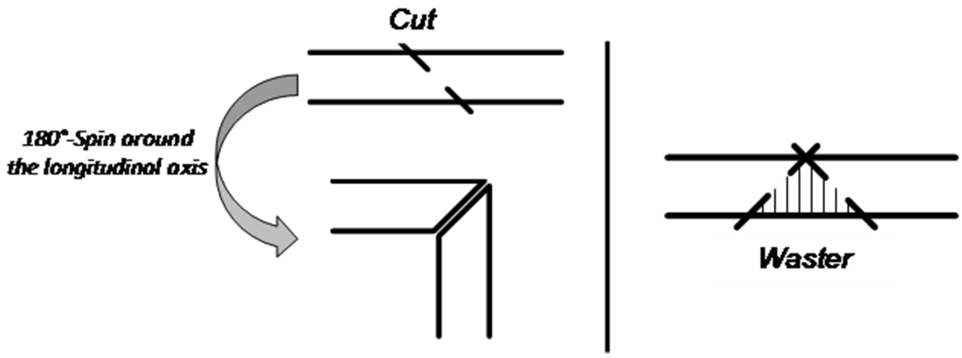

Figure 4. Consequences of symmetric (left) and non-symmetric (right) cross-sections

4.1.2 Structure-topology

Profile-structures are a kind of sequence of individual profile-elements. This requires the optimisation of the assembly structures (the composition of individual elements), the so-called structure- topology.

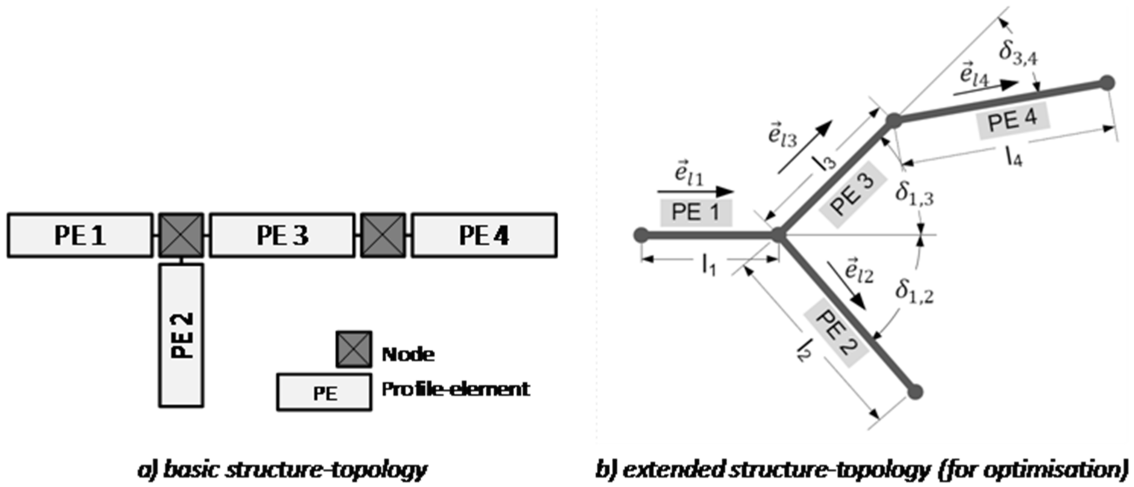

Figure 5. Structure-topology

The structure-topology of profile-structures is modelled as a sequence of straight profile-elements. The profile-elements are connected by nodes. The division into profile-elements allows a free profile design: One sheet metal profile can be modelled from several profile-elements and nodes. Nodes represent the connection between profile elements. Therefore, a node is always between at least two profile-elements. Nodes that connect exactly two profile-elements are called sharp bend. Nodes that

connect more than two profile-elements are called branches or associations. The basic structure-topology is displayed graphically compared to a tree structure (figure 5 a)).
The number of profile-elements and number of nodes are design parameters linked to the entire assembly structure. The usage of a simple structure-topology does not allow an optimisation. Therefore, an extended structure-topology is used. The extended structure-topology includes the main dimensions and the position in space (figure 5 b)).
Each profile-element is described by its arrangement in the assembly (sequence), its position, direction and length. Vectors are used to describe the position and direction of the longitudinal extent. Nodes themselves have no spatial extension. They connect profile-elements with a defined bend angle $\delta_{i,j}$. The location of profile element j (j=i+1) is a result of the properties of profile element i.

$$\vec{p}_{lj} = \vec{p}_{li} + l_i\vec{e}_{li} \qquad (1)$$

The relationship between the bend angle and the direction vectors can also be expressed mathematically. If α defines the angle that includes the first major axis and the first profile-element, the general formula for the direction vector is:

$$\vec{e}_{li} = \begin{pmatrix} \cos(\alpha+\sum_{j=2}^{i}\delta_{j-1,j}) \\ \sin(\alpha+\sum_{j=2}^{i}\delta_{j-1,j}) \end{pmatrix} \qquad (2)$$

Constraints of design space have to be considered in determining the structure-topology. The restrictions have to be described in a formalized way for algorithmbased-optimisation. The following example describes an algorithmbased-optimisation of a structure-topology.

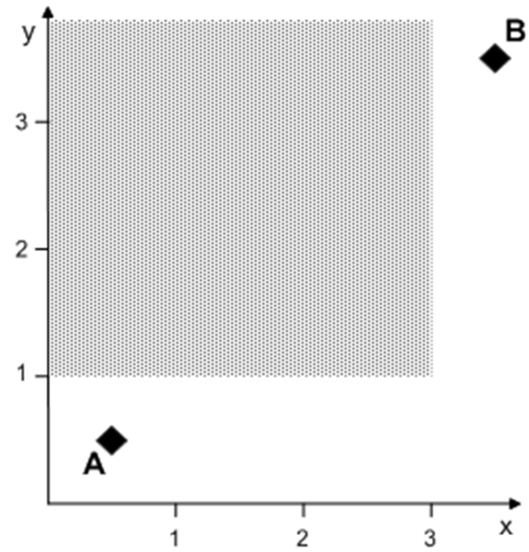

Figure 6. Optimisation of structure-topology: task

A flat, straight profile-structure is to be designed. The two endpoints (A and B) and a constraint of design space (shaded area) are given (figure 6). To minimise the production costs, the use of materials will be minimised as well as additional manufacturing processes: Thus the design parameters are chosen so that the number of nodes and the total length are minimised.
The direct connection between the two points is the version without a bend and with the least total length. This option is contrary to the constraint of design space and is therefore not a solution. The next option being considered has one bend with a very small bend angle. This option violates the restrictions, too. The bend angle will gradually be increased until the restriction is complied with. This option is a valid solution (figure 7 left).
Changing the rules for optimising leads to various results. For example, special bend angles (30°, 45°, 60°, 90°) or the use of the same angles can be set (figure 7 right).

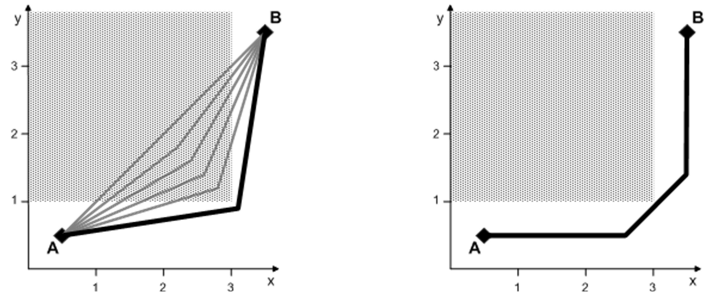

Figure 7. Optimisation of structure-topology: two solutions

4.2 Geometry

The geometry is optimized in the next step on the basis of the determined topology. In addition to geometric properties, the choice of material defines the material properties (e.g. elastic modulus, density). The geometry optimisation is broken down into a cross-section optimisation and a structural optimisation in analogy to the topology.

4.2.1 Assignment of cross-sectional values

Every single profile-element is assigned to cross-sectional values according to the task during structural optimisation. The starting point for the structural optimisation is the structure-topology.

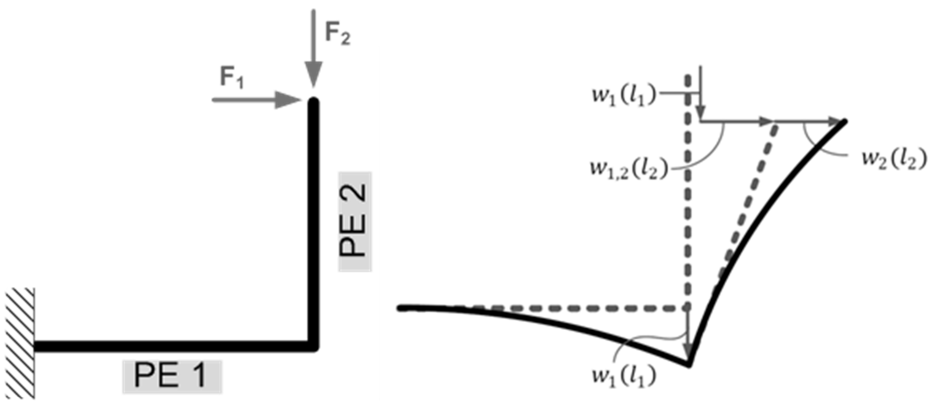

Figure 8. Bending of profile-structures

A profile-structure out of two profile-elements is examined for an exemplification. The two profile-elements are connected with an angle of 90°. One end of the profile-structure is clamped. External forces take effect on the other end (figure 8 left). In determining the geometric properties, make sure that e.g. strength values are not exceeded. Further requirements such as limitations on displacements due to bending may arise from the task at the same time.

The analysis of the deflection of the profile-structure shows that the displacement of the non- clamped end results on the superimposition of three separate displacements. The deflection of the lower profile-element moves the second profile-element downwards. The curvature of the lower profile-element moves the end of the second profile element to the right. Additionally, there is the actual deflection of the second profile-element (figure 8 right).

The value of the bending stiffness of both profile-elements influences the displacement of the second profile-element's end. Thereby, the bending stiffness of the lower profile-element influences the displacement of the second profile-element's end stronger than second profile-element's one. The optimisation of geometry requires the optimal assignment of the moments of inertia for each profile-element. It is easy to imagine that if dealing with more complex structure-topologies the number of influencing variables will increase enormously. A large number of possible assignments of cross-sectional values will exist. Therefore, procedures must be developed to identify the optimum assignment. Basically, the problem is formalized as far as that mathematical optimisation methods can be used for this.

4.2.2 Cross-section optimisation

If each profile-element is assigned to the optimum cross-sectional value, the remaining geometry properties (e.g. thickness) are determined in the second step. The geometry properties are determined, so that the appropriate cross-sectional values are reached and thus the maximum acceptable strength values and displacements (e.g. due to bending or torsion) cannot be exceeded. Within the CRC 666, mathematical optimisation procedures have already been developed that can be extended for the application of profile-structures.

4.3 Technology

Based on the optimised geometry and topology, it has to be examined how the in principle designed profile-structures can be produced optimally. The optimal unrolling of the flow-splitting profile-elements has to be determined. In addition, it has to be decided how the nodes between the profile-elements are produced.

4.3.1 Manufacturing of cross-sections

Each profile has to be checked for its manufacturability and its optimal unrolling needs to be calculated. The decision for a technology is done on each intersection point, e.g. whether to 'joint' or to 'split.' Technical process limitations restrict the possibilities. Mathematical procedures already exist to calculate the optimum unrolling of multi-chambered profiles. They analyse the cross-sectional geometry as a graph-problem.

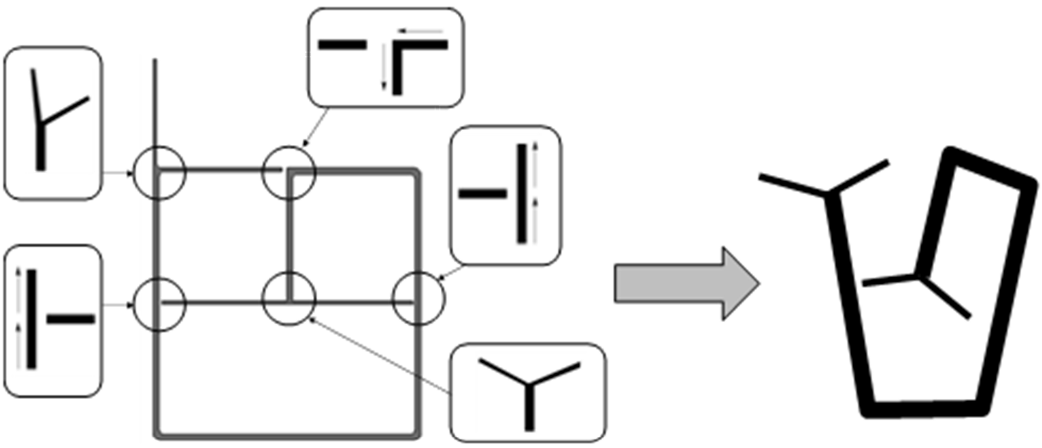

Figure 9. Determination of T-junction technologies

4.3.2 Manufacturing of nodes

Several technologies for the manufacturing of nodes are available (e.g. bending, welding, soldering, gluing, screwing). All these technologies have certain process limitations. Different properties of profile-structures are the results of the different possibilities to manufacture nodes. If nodes are manufactured by bending, the several chambers of multi-chambered profiles are uninterrupted and separated. Welding two multi-chambered profiles cannot ensure this, because the inner chamber walls cannot reached with the welding tool. In addition, other technical limitation exists during bending. For instance, the bending radius cannot be chosen freely. If it is reduced to a level below the limit, which depends on the material and the profile width, cracks will open on the outer fibre or the material will get too thin. With regards to an automated design of profile-structures, the technologies for manufacturing nodes have to be checked on process limitations and properties.

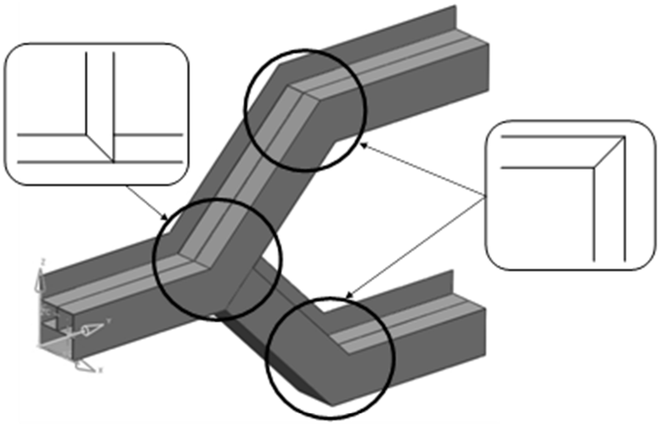

Figure 10. Determination of node technologies

5. Summary and conclusion

This contribution describes a concept for an automated design of profile-structures. The concept includes a gradual approach from the abstract to the concrete. Procedures that have been developed in the first period of CRC 666 can also be integrated in this approach.

Properties of profile-structures, especially design parameters, are identified and they are assigned to each step of optimisation. Main dimensions and the orientation in space, for example, are topological parameters. This assignment transcends the usual understanding of topology.

In principle, the explanation shows that the three-step approach (topology, geometry, technology) is applicable for profile-structures and that it can be supported by mathematical processes. The fact that three different models are used which have to be transferred is a disadvantage of the optimisation of cross-sections of profiles. Therefore, it has to be proven if a consistent model is feasible. Certainly, the object complexity of profile-structures is a great challenge.

The three steps topology, geometry and technology are strongly linked. Based on this reason iterative loops have to be integrated in the systematical search for the global optimal solution. Hence, mathematical optimisation processes have to be developed that allow to realise iterative loops with a manageable effort.

Acknowledgement

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